CONCRETE MIX DESIGN IN THE TROPICS

BY

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S Y N O P S I S

The object of the study was to determine the necessary constituents and proportions of materials required to produce concrete of the desired consistence and compressive strength under tropical climatic conditions. From the results of the investigation, a simple method of concrete mix design, which is suitable for use in the tropical countries, has been evolved. The method is based on the "standard type curves" principles where the aggregate grading is by the specific surface area method.

Concrete mixes were made with various mix proportions using "Elephant" brand of Ordinary Portland Cement, river sand and crushed rock aggregates. The aggregates were combined in three gradings covering the range likely to be required in practice. The main independent variables in the tests are:-

(i) the aggregate gradings - in terms of the specific surface of the aggregates;

(ii) the water/cement ratios - between 0.3 and 0.9 by weight.

(iii) the aggregate/cement ratios - between 3.0 and 9.0 by weight; and

(iv) the ages at test - at 3, 7 and 28 days mainly, but in a few instances at 12 weeks.

The workability, measured by the compacting factor method, and the compressive strength of the mixes were determined and the results have been analysed to give Tables and Curves from which a suitable combination of water/cement ratio, aggregate/cement ratio and aggregate gradings may be easily estimated to give a mix with the required compressive strength and degree of workability.

The experimental results show that the workability of concrete made in the tropics is lower but the compressive strength is higher than those made under temperate climates. The rate of gain in strength is increased on average by about 15 percent. This indicates that the concrete designed strictly using the Road Note No.4 data will most likely under-estimate the strength of the concrete made in the tropics and will lead to uneconomical use of materials.

The proposed design method was compared with others, and suggestions were made for further research on points outside the scope of this investigation.

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1. INTRODUCTION

1.1. TROPICAL CLIMATE:

The hot regions of the world lie roughly between the Tropics of Cancer and Capricorn, Latitudes $23\frac{1}{2}^{o}$ North and South respectively. These are the extreme positions at which the sun appears to be directly overhead at noon. The climatic conditions of these hot regions may be divided into two distinctive types, namely: warm-humid and hot-dry regions; but there are other variants of these, such as equatorial coastal islands, savannah, moonson, semi-desert and maritime-desert..

The warm-humid climates are generally associated with regions near the equator (0^{o} to 15^{o}North or South), such as the Amazon Basin areas of Brazil, Southern part of Nigeria, Ceylon, Singapore and Indonesia. The characteristics of these climates are heavy rainfall, high relative humidity, high wind speed especially in open areas accompanied with squalls and thunderstorms, and mean temperatures of about $70^{o}F$ to $80^{o}F$ ($21^{o}C$ to $27^{o}C$) throughout the year which may, however, reach almost $100^{o}F$ ($38^{o}C$) in the hot season .

The regions of hot-dry climates are found mainly between Latitudes 15° to 30° North or South of the Equator, such as the desert areas of Africa - (Egypt, Algeria, Sudan, Saudi Arabia and Northern part of Nigeria), Mauritania, Argentina, and some other parts of South America. The characteristic features of these climates are high temperature (of up to 120°F (49°C)) with high daily range and seasonal variations of temperature, very hot with intense sunlight days and cool nights, dust storms, little or no rain, very low relative humidity, and high air velocity which may lead to whirlwinds or tornadoes.

Tropical climates consist of two marked seasons: the dry season and the wet season. The dry season, which lasts for approximately six months (October to April , in the Northern Hemisphere) is notable for high temperature combined with low relative humidity together with low rainfall and high air velocity; whilst in the wet season, (May to October), an equatorial type of climate with high rainfall and moderate air velocity persists.

Typical average climatic conditions of Kaduna in northern part of Nigeria where this investigation was carried out are shown in Table 1.

TABLE 1 - AVERAGE CLIMATIC CONDITIONS OF KADUNA-NIGERIA AT THE TIME OF INVESTIGATION (1969/70). *

MONTHS OF THE YEAR 1969/70	TEMPERATURE MAX. °F	TEMPERATURE MIN. °F	RAIN FALL ins.	RELATIVE HUMIDITY (Mean Daily) %	WIND FORCE (m.p.h.) MAX.	WIND FORCE (m.p.h.) MIN.	SUN SHINE hrs.	EVA-PORA-TION ml.
JAN.	88	59	0.00	30	21	10	8.9	19.5
FEB.	96	63	0.00	22	21	10	9.4	20.3
MARCH	99	72	0.00	35	28	5	8.5	14.4
APRIL	94	73	4.40	50	42	10	6.9	8.5
MAY	91	71	3.72	78	42	5	8.1	5.5
JUNE	86	69	5.72	80	35	10	6.8	3.8
JULY	83	68	11.23	85	28	5	6.2	2.6
AUG.	82	68	14.40	89	35	5	4.9	2.0
SEPT.	84	67	12.21	86	35	10	6.8	2.4
OCT.	87	67	5.02	82	28	5	8.4	3.0
NOV.	88	59	0.45	56	21	5	9.0	8,8
DEC.	92	55	0.00	38	15	5	10.3	12.1

* Data supplied by the Metereological Office, Kaduna.

Kaduna lies roughly at Latitude 10.5° North and Longitude 7.4° East, which is in the hot-dry zone of the tropics. As can be seen from Table 1, an average temperature of as high as 99°F (37°C) and a relative humidity as low as 22%, with little or no rain for most months of the year were recorded. The temperature drop during the months of November to February was due to the cooling effects of the harmattan. The lowest temperature was 55°F (13°C), and this often occurred at night.

1.2 HOT CLIMATIC EFFECTS ON CONCRETE:

Some special concreting problems that are uncommon in temperate regions are experienced in the hot regions of the world as a result of the hot climatic conditions. The combined effects of the tropical climatic conditions cause the hardening rate of fresh concrete to be accelerated, a factor which reduces the length of time that concrete remains workable, and increases the tendencies to crack and shrinkage development. The effects of the hot weather conditions on the operative during the mixing and placing of concrete may also indirectly affect the quality of the resulting concrete. It is known that heat causes ills, such as sun or heat stroke and intense fatigue on the operatives. The hot-dry air is more pleasant to work in than the warm-humid one.

It is now clearly established that some of the properties of concrete, such as workability, compressive strength and durability are affected by tropical climates. (1)*

* The numbers in brackets relate to the list of references on page 133.

It is also realised that the concreting problems are mainly caused by the high ambient temperature, accompanied by low relative humidity and high air velocity which result in higher concrete temperature and increased rate of drying out than is the case under temperate climatic conditions. The rapid temperature change between day and night or sudden storm or diurnal ranges of ambient temperature causes abrupt change in the concrete temperature; this subjects the concrete to expansion or contraction which tends to lead to cracking and deformation. Also, the heavy rainfall, high winds of hurricane force and tornadoes, dust and sand storms, and intense solar radiation during the day and dew at night, which are all occurring in varying degrees, will undoubtedly have adverse effects on the durability of concrete unless special measures are taken to protect the concrete.

Hot weather conditions make it extremely difficult to prevent concrete from losing its workability before it is placed. The decrease in workability is due to the high concrete temperature and the rapid drying out of the concrete.

In practice, to compensate for the decrease in workability or the increased loss in slump of concrete placed under hot weather conditions, one of the following methods is adopted by the concrete designers [1,2]:

(i) by increasing the water content of the mix, i.e. increasing the water/cement ratio.

(ii) by increasing the richness of the mix, i.e. reducing the aggregate/cement ratio.

(iii) by using additives in the concrete.

The use of increased water to maintain consistency leads to an adverse effect on strength, as it has been long known from Abram's water/cement ratio law that the strength of concrete greatly depends on the water/cement ratio of the mix. An increase in water/cement ratio causes a reduction in the strength of the concrete.

By increasing the richness of a concrete mix, that is, by increasing the cement content of the mix, the tendency for shrinkage and crack development is aggravated. The higher the cement content in a mix the more rapid and higher the shrinkage of the concrete when the mixing water evaporates. Stiffer mixes are generally recommended for hot weather concreting [1].

The use of a suitable concrete additive is increasingly adopted for hot weather concreting to combat some of its defects. The additives commonly used serve two main purposes:

(a) to reduce the mixing water requirements, and

(b) to retard the hardening rate of concrete.

Many research workers [3] have confirmed the advantageous effects of water-reducing retarders on concrete made under hot weather conditions, and it is likely that its use will continue to increase especially now that some local materials and products such as starch from cassava or corn and sugar have been found to possess water-reducing and set-retarding properties when used in concrete [4].

The importance of the detailed knowledge of these effects of climatic conditions on concrete by the concrete mix designers, cannot be over emphasised. These climatic conditions exert great influence on concrete properties and need to be taken into consideration by the concrete designer while determining the most economic combinations of materials to produce a concrete of the desired properties.

1.3. PREVIOUS EXPERIMENTAL WORK ON CONCRETE IN THE TROPICS.

Many research workers have confirmed that workability of concrete decreases as the temperature of concrete increases and that the rate of gain in strength of concrete mixed and cured under tropical conditions is different from that in temperate climates [5,6,7]. Virtually all experimental results on concrete made and tested in the tropics indicate a rapid gain in strength during the first few days. But different opinions exist as to the effect of hot climatic conditions on the compressive strength at older ages and the ultimate strength of concrete. Some observers record an adverse effect whilst some others noticed the exact opposite. The following are the conclusions of the results of some of the research workers:

The Building Research Station at Ghana[5] reported that the strength of concrete in West Africa is, at all ages, higher than that of a similar concrete cast and cured in a temperate climate; and that, the ratio of 7-day strength to 28-day strength is about 0.75 for medium strength concrete; as compared with a value of 0.67 for a temperate climate.

They found that for a typical mix, the strength at 3 days was about equal to the expected strength at 7 days in a temperate climate.

Ghana's results were in agreement with those obtained in Nigeria by Ackroyd and Rhodes [6] who also reported increased strength at all ages up to 12 months even though the rate of increase after 1 month was very slow for concrete made under tropical conditions.

However, a contradictory result was reported by Ridley [7]. He found that the effect of tropical climatic condition gives a reduction in strength of up to 15% at 28 days when compared with those of the temperate climate. In his view, the Road Note No. 4's[8] crushing strengths cannot be achieved under hot climatic conditions. His experiments were conducted under hot-humid tropical climates at Lagos in Nigeria at an average atmospheric temperature of 86°F (30°C) and relative humidity of 80%; but the specimens were actually cured under water at a temperature of about 70°F (21°C) in accordance with the British Method as specified in B.S. 1881 [9].

Also, Shalon and Ravina [10] who made a study of strengths of concrete under Israel's desert conditions - (similar to hot-dry regions of the tropics), found up to 15% lower strengths at 86°F to 104°F (30°C to 40°C) initial temperatures, as against the specimens made and cured at standard conditions of 68°F (20°C) and 70% relative humidity.

The results of tests on the effect of elevated concrete temperature on strength at a given age depend on the circumstances of the test and the testing method. If the concrete is made under high temperature conditions and allowed to remain there until it is tested the strength is likely to be higher than would have been obtained at a lower uniform temperature; but if warm concrete is allowed to cool and remain at a more normal temperature for most of the time before testing, the strength would probably be lower than would have been obtained if the temperature had been at the lower level for the whole of the time. This statement was confirmed by the results obtained in earlier experiments by the writer[4]; abridged data from the results are shown below:-

Mix Ref. No.	Conditions of Test				Compressive Strength
	Cubes made at Temp.	Cubes Cured Initially at Temp.	R.H.	Finally in water at Temp.	at 7 days
	°C	°C	%	°C	%
1	30	30	45	30	100
2	30	30	45	20	90
3	20	20	90	20	93
4	20	20	90	30	99

The results are based on an average of three tests. It can be seen from the Table that the concrete made and maintained at elevated temperature until test (Mix No.1) had about 7% higher strength than the concrete made and kept at lower temperature (Mix No.3). When the concrete made at elevated temperature (Mix No. 2) was cured under normal temperature until test, the strength was about 3% lower than that of concrete mix made and kept at lower temperature throughout (Mix No.3). There was about 10% reduction in strength of concrete made at elevated temperature but cured at lower temperature (Mix No. 2) compared with the concrete made at elevated temperature and kept there for the whole of the time until tested (Mix No.1).

Mix No. 4 shows about 6% higher strength than Mix No. 3 which indicates that higher temperature is beneficial to compressive strength of concrete.

Since no standard testing method has yet been established for hot weather concreting, it is hard to arrive at a general conclusion as to the effect of hot weather conditions on the strength of concrete.

Low strength may be the result if the water/cement ratio is varied to maintain constant workability, and if the loss of workability due to rapid drying out is not allowed for correctly in the design. Under hot climatic conditions, the severe drying out of the concrete may interfere with the hydration process of cement. The excessive loss of mixing water may make the free water in the concrete insufficient for the hydration process to proceed and cause the strength to stabilise too quickly; consequently, strength development and further strength growth are arrested. But on the other hand, if sufficient free water is available during hydration process, the high temperature of concrete will speed up the action of hydration, and this may lead to an increase in strength. The rapid evaporation of the mixing water may also result in higher strength because if the water that seeps out of the mix due to bleeding

phenomenon is evaporated at early stage, it will lead to a reduction of the effective water/cement ratio, a factor which contributes to an increase in strength of the concrete.

A generalisation may be made on the available experimental data on the effect of temperature on concrete that there is universal agreement as to the beneficial effect on strength of higher than normal temperature at very early ages provided the curing temperature is not lower than the casting temperature. The available evidence so far does not justify a categorical statement for ages above 28 days.

The practical significance of the above conclusion for concrete designers in tropical countries is two-fold: In hot-humid climates, where the temperature variation is small the high temperatures are not likely to have an adverse effect on concrete strength. In hot-dry areas where there is considerable diurnal temperature range, the net thermal effect may cause a loss in strength, particularly for concrete cast in the evening at fairly high temperature followed by a cold night.

1.4 THE SCOPE OF PRESENT INVESTIGATION:

Although the main aim of the present work is to determine the necessary proportions of materials for producing concrete of the desired workability and compressive strength, nevertheless, it has served to throw further light on the controversial issues of the effect of hot weather conditions on strength of congrete.

Some of the previous experimental work on hot weather concreting were based on specimens made under temperate conditions but cured under elevated temperature conditions. It appears that such tests may not give an accurate indication of the effect of tropical climatic conditions on concrete properties as much as it would be if the tests were carried out under the actual hot weather conditions. The present work has been conducted in the laboratory under the actual tropical conditions. The specimens were made and cured at the room temperature.

Up till now, there has been no universally recognised standard method of testing concrete in the tropical countries. Most people are currently working to the Standards laid down for use in the temperate

countries. Such results will not give a direct bearing on what is actually obtained in practice in the tropical countries. The present work has been so designed in order that the procedure followed could be standardised and possibly recommended for adoption as a standard for concrete tests in the tropics.

In the past, the design of a concrete mix is based on design data evolved for use in the temperate countries and very little work has been done by indigenous research workers in the tropical countries to verify the accuracy of such data and to modify them if necessary to suit their own climatic conditions. The present investigation has therefore been conducted in order to produce some design data somewhat similar to the ones currently used, (e.g. Road Note No.4 data), but simpler and easier to use and, it is believed more appropriate for use in concrete mix design in tropical countries.

The experimental work was conducted on materials normally available locally and the tests cover the range likely to be required in practice. The main factors considered in the tests are the specific surface of the aggregates, the water/cement ratio and the aggregate/cement ratio. Various proportions of materials were combined to produce concrete of which the workability

and compressive strength were tested. The main independent variables in the tests were:-

(a) The Aggregate Grading :-

Three aggregate gradings were established. The total specific surface of the combined aggregates for the three gradings were 635, 827 and 1111 respectively. The aggregate proportions for these gradings by weight were:-

band: $\frac{3}{8}$" aggregate: $\frac{1}{4}$" aggregate,

$22\frac{1}{2}\%$: $22\frac{1}{2}\%$: 55%, for grading No. 1,

30% : 25% : 45%, ,, ,, ,, 2,

43% : 22% : 35%, ,, ,, ,, 3.

(b) The Water/Cement ratio :-

Ranges between 0.3 and 0.9, by weight.

(c) The Aggregate/Cement ratio :-

Varies between 3.0 and 9.0, by weight.

(d) Ages at Test :-

The cubes were tested at 3, 7 and 28 days mainly, but in a few instances at 12 weeks.

The variables were investigated in limited combinations in order that their effects could be more accurately determined. For example, the water/cement ratio was kept constant and the aggregate/cement ratio varied accordingly for a particular aggregate grading.

The tests were designed so that each series of the test was completed using the same consignment of materials as far as practicable; but this was not always possible in the case of the cement supply because this was received in bags.

The details of the mixes and the outline description of the tests are shown in Table 2.

Because of the intractable programme that will be involved, the experimental work had to be restricted, hence the following aspects were outside the scope of the present work.

(a) The use of other brands of cements available locally, e.g. Sokoto Cement.

(b) The use of other types of coarse aggregates locally available, e.g. Land gravel.

(c) Tests at older ages.

(d) Tests conducted under actual site conditions.

Test using Sokoto cement has recently been studied by another investigator [11]. The other three aspects will be subjects for recommendation for further research work.

TABLE 2 - DETAILS OF MIXES AND OUTLINE DESCRIPTION OF TESTS:

MIX PROPORTIONS:

Mix Series	Sand:	$\frac{3}{8}$"Agg.:	$\frac{3}{4}$"Agg. (%)	Total Surface Area.
Preliminary Mixes	30 :	30 :	40	832
Grading No. 1	$22\frac{1}{2}$:	$22\frac{1}{2}$:	55	635
,, ,, 2	30 :	25 :	45	827
,, ,, 3	43 :	22 :	35	1111

Mix Serial No.	Description of Tests.
T.M. Series	Trial Mixes Materials were combined in various proportions. Sieve analyses of each combination were made and compared with gradings of Road Note No.4. Concrete was mixed by hand and mix observed for cohesiveness, homogeneity, and ease of handling. 15 mixes were made and two 4" cubes cast for test at an age of 7 days. The results are shown in Table 6.

Mix Serial No.	Description of Tests.
P Series	<u>Preliminary Mixes</u>: The slump test and compacting factor test were conducted on 19 mixes, having water/cement ratio ranging from 0.4 to 0.8 and aggregate/cement ratio between 3.0 and 8.0. Nine 4" cubes were cast from each mix, three being tested at ages of 3, 7, and 28 days respectively. The results are shown in Table 7.
A Series	<u>MAIN TESTS</u> <u>1st Tests</u>: Mixes were made with aggregate grading No.1, having water/cement ratio range of 0.3 to 0.9, and aggregate/cement ratio between 3.0 and 9.0. The compacting factor test only was conducted. 25 mixes were made, and nine 4" cubes cast from 21 of them and tested at ages of 3, 7, and 28 days; three 6" cubes were cast from the remaining 4 mixes, and tested at an age of 28 days. The results are shown in Table 8(A) and 8(X).

Mix Serial No.	Description of Tests
B Series	Mixes were made and tested as in A-Series but aggregate combinations were in grading No.2. The results are given in Table 8(B) and 8(X).
C Series	Mixes were made and tested as in A-Series but aggregate combinations were in grading No.3, 31 mixes were made, and nine 4" cubes cast from 27 mixes and three 6" cubes cast from the remaining 4 mixes. The results are given in Table 8(C) and 8(X).
Check Mixes	2nd Tests: A check on the 28-days strength results obtained in Series A to C above. For Grading No. 1 - 15 mixes were made, and three 4" cubes cast for test at 28 days; and a fourth cube was cast out of three of the mixes and tested at the age of 12 weeks. For Grading No. 2 - 13 mixes were made and tested as in grading No. 1. For Grading No. 3 - Mixes and tests as in Grading No.1. The results are given in Table 9.

Mix Serial No.	Description of Tests
Check Mixes	3rd Tests: A check on the 3 and 7 days results obtained in C-Series of the 1st. tests. 17 mixes were made, and six 4" cubes cast, three cubes being tested at ages of 3 and 7 days respectively. One test was conducted for mixes in grading No. 1 and 2 using the same consignment of cement as used in grading No. 3. The results are shown in Table 10.
Check Mixes	4th Tests: Check on 28 days strength to confirm the effect of aggregate grading. 10 mixes were produced from each of the three aggregate gradings and three 4" cubes cast for test at an age of 28 days. The results are shown in Table 11.
Check Mixes	5th Tests: Spot check on the workability and strength results for each aggregate grading. Mixes were made having low and high degrees of workability.

1.5. REVIEW OF CONCRETE MIX DESIGN METHODS

The purpose of designing a concrete mix is to produce the desired properties and qualities in concrete by the most economical and practical combination of the available materials. The process of proportioning the available materials may be entirely empirical and depend on experience or observation alone, or it may be based on technical tests and calculations. There are several different methods of mix design proposed by different research workers especially in the temperate countries, and some of these will be briefly reviewed here.

(i) The Arbitrary Proportions Method:

The simplest method is the "Arbitrary Proportions Methods", which is based on the proportioning of the materials in the form of parts or ratios of cement, fine aggregate, and coarse aggregate; with cement taken as unity. The mix is normally expressed on the basis of 1: n: 2n, such as 1: 2: 4 mix; and to be definite, the basis of the proportions are often stated, for example, by weight or by volume.

In this method, fixed quantities of fine and coarse aggregates are mixed without regard to the size and grading of the individual materials.

The method also assumes that the strength of the concrete is determined solely by the water/cement ratio, and that the workability for a particular water/cement ratio is dependent mainly on the aggregate/cement ratio. These two assumptions are not always entirely true. Other factors such as the aggregate size, shape, surface texture and grading have a remarkable effect on workability, and also the aggregate/cement ratio exert a considerable influence on the strength of concrete.

This method is simple to use but often provides poor control of the workability of the concrete mix; however, its use has been found to be satisfactory for ordinary grade concrete.

(ii) The British Design Methods.

The best known and most widely used methods of mix design in Britain is the one described in Road Note No.4 [8], whose data are now brought to date by recent research workers [12], The method is based on approximations to type grading curves designed to give good results of workability and strength with normal aggregates.

The grading curve of the combined available aggregates is made to approximate some predetermined standard grading curves for which the relationship between the aggregate/cement ratio and workability is known for a particular water/cement ratio.

The design procedure briefly consists of the following steps:

1. Decide the minimum compressive strength for the job.
2. Estimate the average strength required to give this minimum strength based on the degree of control anticipated. (The necessary ratio may be derived from a given Table; or may be calculated by using either the 'standard deviation' or ' coefficient of variation' formulae.)
3. Read off the water/cement ratio to give the necessary average compressive strength from a given Figure.
4. Decide on the degree of workability required for the conditions of placing; using a given Table as a guide.

5. Decide the grading curve to follow having considered the type and maximum size of the available aggregates.
6. Determine the aggregate/cement ratio required to give the selected degree of workability and grading at the predetermined water/cement ratio from a given Table.
7. Proportion the different sizes of aggregates to approximate given standard grading curves.
8. Make trial mixes and adjust the mix proportions if desirable.

This process of mix design is modified by Erntroy and Shacklock [13] for use in designing high-strength concrete. In this method, the aggregate/cement ratio and the workability are chosen first before the water/cement ratio for a required strength is determined. The method also assumes that a very high compactive effort with a very dry mix will be used rather than attempt to maintain high workability by using a very rich mix.

There are two main objections to the use of the type-grading curve method:

(a) it is not always possible or economical to grade the available materials to conform with any of the standard curves.

(b) the best approximation with the type curves does not always give the best results under all conditions. For example, aggregates of the same overall gradings may produce concrete of different workability.

(iii) The American Method of Mix Design:

The method described here is based on the American Concrete Institute's recommended practice for selecting proportions for concrete [14]. The features of the methods are:

(a) that over a considerable range of practical proportions, fresh concrete of a given slump and containing reasonable well-graded aggregates of given maximum size will have practically constant total water content regardless of variations in water/cement ratio and cement content.

(b) that the optimum ratio of the bulk volume of coarse aggregate to the total volume of

concrete depends mainly on the maximum size of the coarse aggregate and the fineness modulus of the fine aggregate. This relation is indicated in a given Table.

The design procedure is briefly as follows:

1. Select the consistency in terms of slump that is appropriate to the conditions of placing, from a given Table.
2. Determine the maximum size of aggregate recommended for the type of construction from a given Table.
3. Read off the total water in gallons per cubic yard of concrete from a given Table, employing the selected slump and maximum size of aggregate values determined in 1 and 2 above.
4. Choose the water/cement ratio (in gallons per sack of cement) that will satisfy both the strength and durability requirements, from given Tables.
5. Calculate the cement content by dividing the total water content by the water/cement ratio.
6. Determine the bulk volume of coarse aggregate per unit volume of concrete for the particular maximum size of aggregate and the fineness modulus of sand, from a given Table.

Compute the solid volume of coarse aggregate per cubic yard of concrete from the specific gravity and weight of the aggregate.

7. Calculate the solid volume of sand by subtracting from the total volume of concrete the solid volumes of cement, coarse aggregate, water and air.
8. Calculate the quantities of materials per batch on the basis of dry aggregates.
9. Make trial mixes and adjust if necessary to meet the requirements of consistency in the field.

The method is claimed to have the advantage of simplicity in that it applies equally well and with identical result to rounded or angular coarse aggregate, to regular or light weight aggregates and to air entrained or non-air entrained concretes.

(iv) The Swedish Method of Mix Design

The method of mix design discussed here is based on the Swedish Cement and Concrete Institute's recommended practice as contained in Alexanderson's paper [15]. The method takes into account the water/cement ratio, aggregate grading by fineness modulus method, and volumetric method of mix proportioning.

It is based on the assumption that if consistence and grading of the aggregates are maintained there is direct relationship between the volumetric proportions of the aggregate and the water/cement ratio.

The outline of the design procedure is briefly as follows:

1. Decide water/cement ratio and if applicable the air content also. Select type of cement.
2. Determine the required consistence and grading.
3. Calculate the fineness modulus for the grading decided.
4. Using the calculated fineness modulus value and the required consistence, a value is either read directly from the design chart or calculated from a given formula. This value is an asymptote of the curve representing the quasi-hyperbolic relationship derived in the experimental study.
5. Fit the hyperbolic "Mix Design Curve" (printed on a transparent plastic sheet provided with the design charts and data) over the mix design diagram and correctly position it according to the asymptotic value as determined in 4, and the value of the air content, consistence and water/cement ratio as previously established.

6. Read off directly the composition of the mix, that is, the cement content in kg/m^3, water content in l/m^3, and the volumetric proportions of the aggregate plus air.
7. To exclude the air content from the aggregate content an adjoining supplementary nomograph is used or the aggregate content may be calculated by substituting the pre-determined value of air content.
8. Calculate the quantity of aggregate in kg/m^3 by multiplying the volume by the density of the aggregate.
9. Determine the batch proportions and carry out trial mix.

The method is said to be applicable to both ordinary strength concrete and cement mortar; and the method permits the properties of the cement and the air content of the mix to be taken into account.

2. MATERIALS AND APPARATUS

2.1. MATERIALS USED.

All the materials used for the concrete mixes are available locally and are commonly used in general construction work in this part of the country. They include the following:-

(i) CEMENT:

The cement was "ELEPHANT" brand of Ordinary Portland Cement made to the requirements of B.S.12 (16), and is produced by the "West African Portland Cement Company Ltd." at their Ewekoro Works in Abeokuta, Western Nigeria.

The chemical composition and physical properties of the cement are listed in Table. 3.

(ii) AGGREGATES:

The fine aggregate used is a river sand obtained from River Kaduna. The sand falls in Zone 2 grading of B.S. 882 (17). The sand was free of silt, clay and other impurities. It was dried and sieved to remove materials greater than 3/16".

The coarse aggregate was a two single-sized ($\frac{3}{4}$" - $\frac{3}{8}$" and $\frac{3}{8}$" - 3/16") crushed rock obtained from Kabala quarry at Kaduna. The stones were washed free of dust, dried and sieved to the required sizes before use.

All the aggregates used in this investigation were from the same source. Immediately they were received, they were kept in bunkers at room temperature before samples were taken, washed and dried, and stored in covered steel storage bins inside the laboratory. The aggregates were used in air-dry condition.

The properties of the aggregates as determined are listed in Table 4. The properties meet the requirements of B.S. 882. The grading curves of the aggregates are shown in Figure 1.

(iii) WATER:

Clean mixing water used was obtained directly from the drinking tap. It is therefore, suitable for making concrete as described in B.S. 3148 [18].

TABLE 3 - PROPERTIES OF CEMENT.

PATENT NAME OF CEMENT - "Elephant" brand of Ordinary Portland Cement.

SUPPLIERS - The West African Portland Cement Co. Ltd., Lagos.

CHEMICAL COMPOSITION:

Constituents	% by Weight.
Ca O	65.10
Si O_2	18.93
Al_2 O_3	6.70
Fe_2 O_3	3.60
Mg O	1.40
S O_3	2.55
I. R.	0.20
L.O.I.	1.49
Undetermined	0.03
Total	100.00

COMPOUND COMPOSITION:

Compound	% by Weight
C_3 S	57.77
C_2 S	10.69
C_3 A	11.64
C_4 AF	10.94

PHYSICAL PROPERTIES.

FINENESS OF GRINDING - Residue on Sieve No.170: 12%.
Specific Surface: 3050 sq.cm/gm.

SETTING TIME-INITIAL - 2 hours 45 minutes.
FINAL 4 hours 50 minutes.

SOUNDNESS - Expansion: 2 mm.

COMPRESSIVE STRENGTH -

Tests	3-days	7-days
4" Concrete Cubes	3000	4000
2.78" Mortar Cubes	4250	5800

BULK DENSITY (Loose) - 90 lbs./cu.ft.

SPECIFIC GRAVITY - 3.0

TABLE 4 - PROPERTIES OF AGGREGATES.

DESCRIPTION OF AGGREGATES

FINE AGGREGATE - River Sand, Zone 2 Grading.

COARSE AGGREGATE - Crushed Rock Granites in two single sizes: (¾" - ⅜") and (⅜" - 3/16")

PHYSICAL PROPERTIES

Properties		¾"Agg.	⅜"Agg.	Sand
Bulk Density - (Loose) (Lb./Cu.ft.)		90.6	85.5	96.3
Voids Ratio	(%)	45.0	48.0	41.0
Angularity Number	(No.)	7.6	12.5	-
Specific Gravity (Oven-dried Basis)	(No.)	2.64	2.62	2.61
Moisture Content	(%)	0.0	0.0	0.0
Water Absorption	(%)	0.2	0.3	0.5
Flakiness Index	(%)	2.5	19.0	-
Elongation Index	(%)	12.6	31.3	-
Impact Value	(%)	14.5	18.4	-
Crushing Value	(%)	17.3	19.8	-

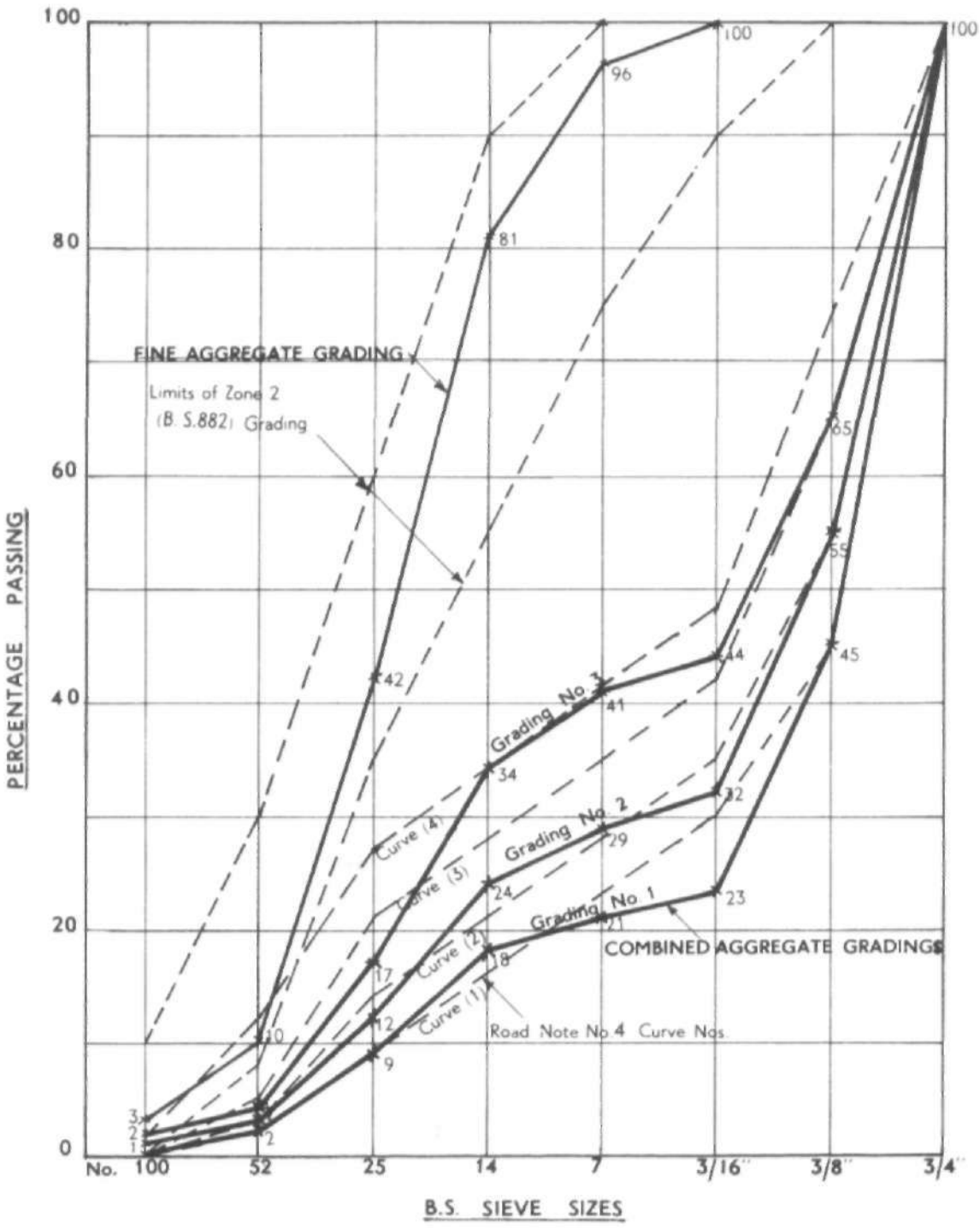


FIGURE 1 – AGGREGATE GRADING CURVES

2.2. APPARATUS AND EQUIPMENT USED

The apparatus and equipment used are the commonly used ones for making concrete tests as described in B.S. 1881. They comprise the following:-

(i) WEIGHING AND MEASURING APPARATUS:

The dry materials used were weighed on a 10kg. capacity scale and the mixing water was measured in graduated measuring cylinders.

(ii) AGGREGATE GRADING APPARATUS:

Sieves comprising of B.S. sieve sizes of $\frac{3}{4}$", $\frac{3}{8}$", and 3/16", Nos. 7, 14, 25, 52 and 100, were used for determining the gradings of coarse and fine aggregates respectively.

The sieves were nested in order and clamped down on a sieving machine which has a time switch incorporated on it.

(iii) CONCRETE MIXING EQUIPMENT:

A 2 cub.ft. capacity horizontal pan-type mixer was used throughout the tests. The hand tools used for mixing and handling the concrete included trowels, scoops and steel floats.

(iv) WORKABILITY TEST APPARATUS:

(a) Slump Test Apparatus

In the preliminary test, the slump test was conducted using a slump test apparatus consisting of a frustrum of cone-shaped mould, having an upper diameter of 4-in, a lower diameter of 8-in. and a height of 12-in. The apparatus was placed on a flat non-absorbing surface during the test. The rod used for tamping the concrete is of $\frac{5}{8}$-in. in diameter, 2ft. long and rounded at one end.

(b) Compacting Factor Test Apparatus:

The compacting factor apparatus is the small type commonly used for laboratory tests and when the maximum aggregate size does not exceed $\frac{3}{4}$-in. The detailed sketch of the apparatus is shown in Figure 2.

(v) CUBES-CASTING EQUIPMENT:

4" steel moulds were used for most of the tests but in some cases 6" ones were used. The moulds were thinly coated with mould oil before use.

A 6ft. by 3ft. electrically operated vibrating table was used for compacting the cubes.

(vi) CURING FACILITIES

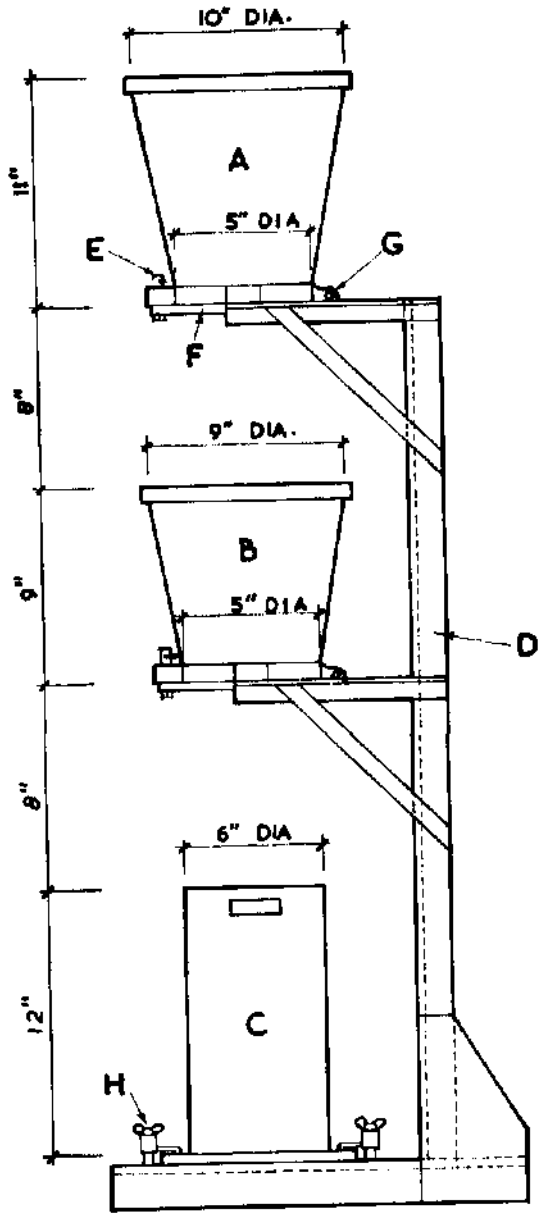
Initial Curing - Polythene sheet was used to cover the top of the cubes (to prevent loss and gain of moisture) and damp hessian used to cover the moulds.

Final Curing - A 24 cub.ft. capacity curing tank was used to store the cubes until test. A pump is attached to the side of the tank to facilitate emptying of the tank for cleaning, and it has a removable lid.

(vii) COMPRESSION TESTING MACHINE:

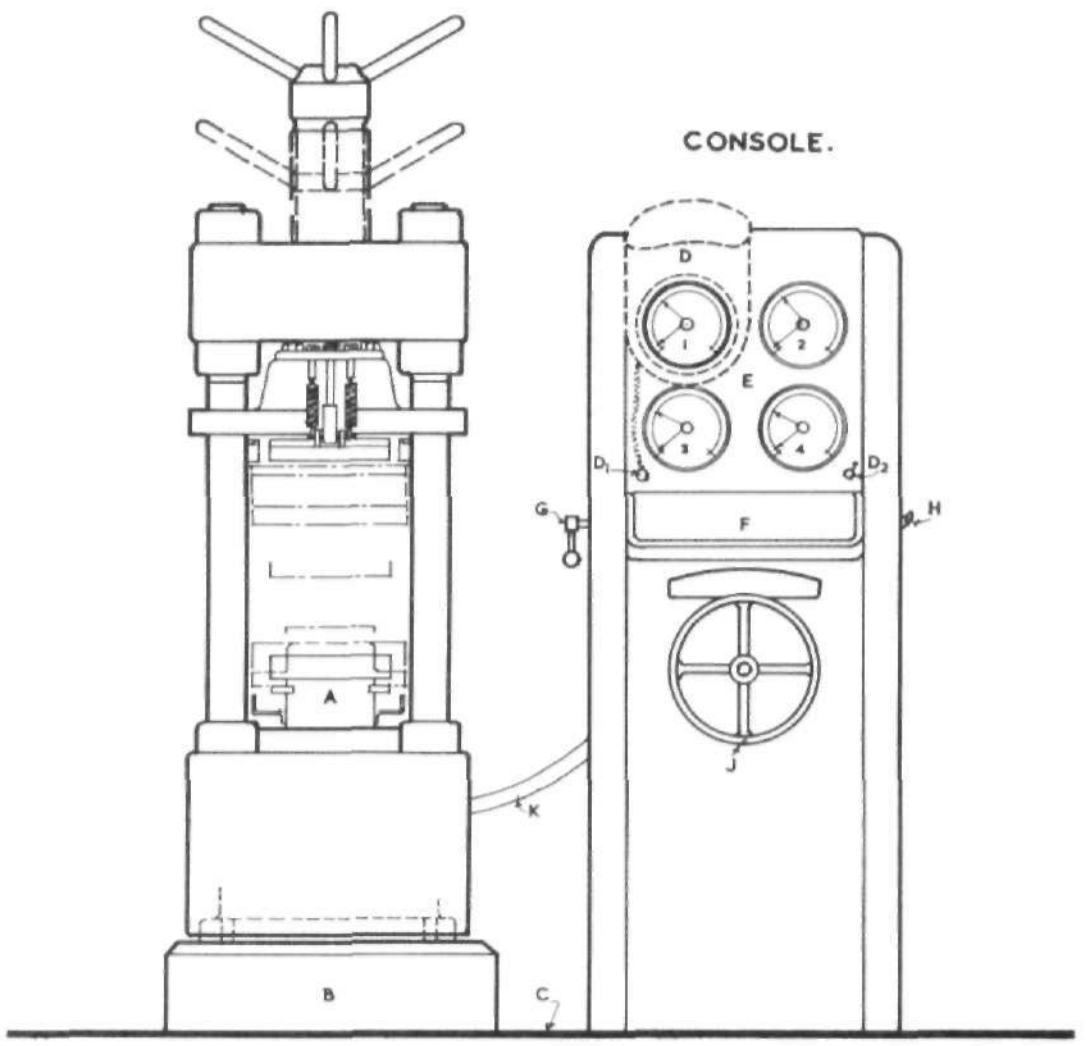
For the preliminary tests, a 100-tons capacity 'Avery' hydraulic hand operated crushing machine was used for the compressive strength tests. The machine has no means of controlling the rate of loading of the specimens and its accuracy was also doubted, hence it was necessary to transfer the tests, to a 'Denison' testing machine.

The Denison's 200-tons hydraulic compression test machine which is electrically operated and incorporated with a pace-setting device to facilitate the control of the rate of loading, was used for all of the main tests. The sketch of the machine is shown in Figure 3.



A-TOP CONNICAL HOPPER.
B-LOWER CONNICAL HOPPER.
C-CYLINDRICAL MOULD.
D-MOUNTING FRAME.
E-RELEASE CATCH FOR FLAP.
F-TRAP DOOR FLAP.
G-HINGE FOR FLAP.
H-CLAMPING SCREWS.

FIGURE 2 - COMPACTING FACTOR APPARATUS.



A - TESTING BED FOR COMPRESSION & TRANSVERSE SPECIMENS.
B - CONCRETE BASE.
C - FLOOR.
D - LOAD PACER ATTACHMENT.
D_1 - LOAD PACER PLUG.
D_2 - LOAD PACER SWITCH.
E - 4 No LOAD GAUGES.

GAUGE NO	RANGES lbs.	DIVISIONS lbs.
1	0 - 448,000	2,000
2	0 - 448,000	2,000
3	0 - 110,000	500
4	0 - 22,000	100

F - CONTROL PANEL INCORPORATING:
4 No GAUGE ISOLATING VALVES.
PUMP DELIVERY INDICATOR.
LOAD APPLICATION FINE STRAINING CONTROL.
MOTOR "ON" INDICATOR.
ISOLATOR "ON" INDICATOR.
MOTOR PRESS BUTTON SWITCHES.
G - RAM CONTROL VALVE.
H - ISOLATING SWITCH.
J - PUMP CONTROL HANDWHEEL.
K - FLEXIBLE RUBBER PIPE.

FIGURE 3 - COMPRESSION TESTING MACHINE.

3. EXPERIMENTAL PROCEDURE:

3.1. PREPARATORY WORK:

Preliminary experimental work was carried out to decide upon the standard of the tests and to establish the programme of the mixes. The following procedures were followed in the tests:

(i) Aggregate Grading

Several aggregate combinations were tried before the standard gradings were established. The sieve analysis tests of the individual aggregates were carried out. Several aggregate proportions were combined and sieved so as to compare the resulting grading with the desired gradings approximating to those of Road Note No. 4. Figure 1 shows the final aggregate grading curves adopted in this investigation. The figure gives the percentage of the aggregate particles passing different sieve sizes as determined by the sieve analysis tests. The British Standard Specification's gradings for sand, and Road Note No.4's gradings for combined aggregates have been included for comparison.

Both the graphical and arithmetical methods as described in Advisory Note No. 9 [19] were used for estimating the required proportions of the aggregates. The arithmetical method is based on the principles of specific surface of the aggregates as described in Section 6 of this report. Arbitrary surface area indices were used in calculating the surface area of each size of aggregate and various aggregate proportions were tried until the sum of the surface areas was approximate to the total of the surface areas of the desired gradings of Road Note No.4. Detailed calculations of the total surface area values for the combined aggregates are shown in Table 5. The total specific surface area values for gradings used in Road Note No.4 are included in the Table for the purpose of comparison.

TABLE 5 - DETERMINATION OF SURFACE AREA VALUES FOR COMBINED AGGREGATES.

B. S. Sieve Sizes	Surface Area Index	Grading No.1		Grading No.2		Grading No.3	
		% Retained	S. A. Value	% Retained	S. A. Value	% Retained	S. A. Value
¾"	-	0	-	0	-	0	-
⅜"	1	55	55	45	45	35	35
3/16"	2	23	46	25	50	22	44
No.7	4	1	4	1	4	2	8
14	8	3	24	5	40	6	48
25	16	8	128	11	176	17	272
52	32	8	256	10	320	14	448
100	64	2	128	3	192	4	256
Total		100	641	100	827	100	1111
Total S.A. Values for Road Note No.4's Gradings:			633		825		1109

(ii) Tests on the Properties of Materials Used:

The properties of all the materials used in the investigation were tested by the methods and manners specified in the relevant British Standard Specifications and are basically as follows:-

(a) CEMENTS:

The properties of the cement used in the mixes were tested in accordance with the requirements of B.S.12[2].

The following tests were carried out:

Properties		Methods of Test
Fineness of Grinding	-	By sieve analysis tests. (sieving through B.S.Sieve No.170).
Setting Time	-	By Vicat apparatus test.
Soundness	-	By Le-Chatelier apparatus test. (determining expansion after 1 hour boiling).
Specific Gravity	-	Using specific gravity bottle.
Bulk Density (Loose)	-	By determining the weight of cement to fill a 1/10 cu.ft. measure.

3.2. PRELIMINARY MIXES:

(i) Trial Mixes Series:

Trial mixes were made from a number of gradings to establish the range likely to be required in practice. The mixes were based on the sieve analysis tests made on various aggregate combinations. The concrete mixes produced were carefully observed for cohesiveness, workability and the tendency towards segregation. As a result of the observation made the three gradings selected were established. The limits of the gradings chosen were based on the characteristics and the appearance of the concrete.

(ii) Preliminary Test Series:

Preliminary mixes were conducted on a full scale trial on one of the gradings proposed. The object of the preliminary mixes is to establish the standard to be followed during the main tests and also to give an indication of the trends that the results may take; from which it was possible to decide on the standard concrete mix design to adopt.

The workability of the preliminary mixes was determined by both the slump test and the compacting factor methods. The two tests were performed on the same mix, the slump test being conducted first. The slump test was started immediately the mixing of the concrete was finished and completed at about 5 minutes after mixing. The concrete was returned to the mixer and remixed with the rest which was covered with a polythene sheet to prevent evaporation of the mixing water. Care was taken to avoid loss of water and of materials. The compacting factor was conducted without delay and it was completed by 20 minutes after mixing. On completion of the test, the concrete was re-mixed by hand with the remainder of the batch in the mixing pan and concrete cubes were cast not later than 40 minutes after mixing. Nine 4-in. cubes were made from each mix, three of which were tested at ages of 3, 7 and 28 days respectively.

3.3. MAIN TEST PROCEDURE:

The preliminary test procedure was slightly modified in the main test series. The workability of the mixes was measured by the compacting factor method only, having found the test more reliable and accurate than the slump test. Further discussion on the merit of each method is contained in section 6 of this report.

Concrete mixes with aggregate/cement ratios of 3.0, 4.5, 6.0, 7.5 and 9.0 by weight and water/cement ratios of .30, .35, .40, .45, .50, .55, .60, .70, .80, and .90 were made for each of the three selected aggregate gradings.

Every care was taken to treat each batch of the mixes in the same way in order to reduce the variability of results to a minimum. Standard mixing and cube-casting procedures were maintained throughout the mixes. For example, from the start of the mixing, water was added to the mix after 2 minutes; the mixer was stopped after 5 minutes; the compacting factor test was commenced immediately after remixing the concrete by hand in the mixer pan. The weight of the partially compacted

concrete was taken by the 8th minutes, and the fully compacted weight recorded by the 15th minutes. Immediately the compacting factor test was completed, the concrete was re-mixed and cubes casted; in most cases, the cube-making was completed within 30 minutes from the start of the mix.

The following procedure was followed in the making and testing of cube specimens:

(i) Batching of Materials:

All the concreting materials were batched by weight to an accuracy of $\frac{1}{2}$ gm except the mixing water which was measured by volume to an accuracy of 1 c.c.

(ii) Mixing of Concrete:

The concrete was mixed by machine in a pan type mixer. The mixer was first charged with the dry materials in the order of sand, cement, 3-in. aggregates, and $\frac{3}{8}$-in. aggregates and mixed dry for two minutes before the water was added. During this period the mixture was of a uniform colour and the aggregates were uniformly distributed throughout the mix. A further mixing for three minutes was carried out after the water had been added, so that the total mixing time was 5 minutes. This length of time permits homogeneous mixes to be attainable.

(iii) Workability Test:

The workability test was carried out immediately after mixing by the compacting factor method. The procedure followed is strictly in accordance with the methods specified in B.S. 1881.

After carefully filling the upper hopper of the apparatus with concrete, the door at the bottom of the hopper was released so as to allow the concrete to fall into the middle hopper. The door at the bottom of this second hopper was also released to permit the concrete to fall into the cylinder below it. The excess concrete was then cut off from the cylinder and the "partially compacted weight" of the concrete in the cylinder was determined to the nearest $\frac{1}{2}$ gm. The corresponding "weight of fully compacted" concrete was also determined by filling the cylinder in six equal layers and compacting each layer on a vibrating table. The compacting factor was then calculated for each mix from the formula:

$$\text{Compacting Factor} = \frac{\text{Partially Compacted Weight}}{\text{Fully Compacted Weight}},$$

(iv) Casting of Cubes:

The concrete mix used for the workability test was remixed with the remaining batch and was used to make the test cubes. Due care was taken to avoid loss in the mixing materials during the test.

The 4-in. cube moulds were filled with concrete and compacted in two equal layers on the vibrating table. Each layer was compacted until no air bubble appeared on the top of the concrete. After the top layer had been compacted the surface of the concrete was trowelled level with the top of the mould. Nine 4-in. cubes were made in the series required to be tested at 3, 7 and 28 days, and six in series requiring 3 and 7 days tests and three in the case of 28 days tests only.

(v) Curing of Cubes:

The cubes were covered with polythene sheets to prevent gain of moisture from the damp sack used to cover the moulds. The cubes were marked on the top with their appropriate identification numbers and carefully demoulded after 24 $\pm \frac{1}{2}$ hours from mixing.

The cubes were immediately submerged in · clean water in the curing tank where they remained until just prior to the test. The curing tank was kept in the laboratory and covered; the temperature of the water in the tank was virtually the same as the ambient air temperature. The curing water was changed regularly.

(vi) Testing of Cubes:

In all the cases three cubes were tested at the desired ages. The ages were calculated from the time of addition of water to the mix ± 1 hour. At the end of each age, the cubes were removed from the curing tank, the surface wiped dry of water and grit, and weighed. The cubes were placed in the testing machines in such a way that the load could be applied centrally to the opposite sides of the cubes as cast. The machine has a pace-setting device by which its rate of loading is controlled. The loading rate maintained was about 2,000 lb./sq. in./min. The maximum load at which the cubes failed was then recorded to the nearest 10 lbs. The appearance and type of failure of the specimens were noted.

4. TEST RESULTS

The results of all the tests are tabulated in Tables 6 to 13.

The results of the Trial Mixes tests are shown in Table 6. The Table gives the observations made together with the cubes test results for various aggregate proportions tried before the aggregate grading adopted in this investigation could be established.

Table 7 gives the results of the Preliminary Test carried out to standardise the test procedures. The results of the workabilities (by both the slump tests and the compacting factor tests), the densities and compressive strengths at ages of 3, 7 and 28 days are shown in the Table.

The main test results are shown in Table 8 to 13 The results of the first series of tests are shown in Table 8(A) for grading No.1, in Table 8(B) for grading No.2, and in Table 8(C) for grading No.3. Each Table gives the workabilities (by compacting factor test), the densities and compressive strengths at ages of 3,7 and 28 days for various water/cement ratios and aggregate/cement ratios combinations.

The results of the compacting factor tests, the densities and compressive strengths at 28 days for each of the three aggregate gradings conducted on the 6-in. cube specimens are shown in Table 8(X).

Table 9 shows the results of the second series of tests undertaken to check the 28-day strength results obtained in the first series. The results of the densities and compressive strengths at the age of 28 days for various water/cement ratios and aggregate/cement ratios are shown for the three aggregate gradings. The results obtained for the densities and compressive strengths at the age of 12 weeks, are shown in brackets under the appropriate mixes.

Table 10 shows the results of the third series of tests taken to check the compressive strength at early ages for the aggregate grading No.3 series. The Table gives the densities and compressive strengths at ages of 3 and 7 days for the various water/cement ratio and aggregate/cement ratio combinations. The results obtained using the same consignment of cement as used in the grading No.3 series, for the grading No.1 and 2 are indicated in the Table.

Table 11 shows the results of the fourth series of tests conducted to confirm the effect of the

aggregate gradings on the strength using cement from the same consignment. The densities and compressive strengths at the age of 28 days for various water/cement ratio and aggregate/cement ratio combinations for grading Nos. 1, 2 and 3 are given in the Table.

Table 12 gives the results of the fifth series of tests taken to check the workability and the strength results of each aggregate grading obtained in the first series of tests. The compacting factor results, the densities and compressive strengths at the ages of 7 and 28 days; and the two ranges of workability ('LOW' and 'HIGH') observed are shown in the Table.

Table 13 shows the results of the sixth series of tests conducted also to verify the effect of aggregate grading on the workability and strength using cement from the same consignment. The compacting factor, the densities and compressive strengths at an age of 28 days for various water/cement ratio and aggregate/cement ratio combinations, for each of the grading Nos. 1 to 3 are given in the Table.

TABLE 6 - RESULTS OF TRIAL MIXES TESTS.

MIX DETAILS			AGGREGATE PROPORTIONS			DENSITY (Lb./Cu.ft.)	COMPRESSIVE STRENGTH (Lb./Sq.in.)	REMARKS
REF. No.	W/C Ratio	A/C Ratio	Sand	⅜"Agg.	¾"Agg.	7-days	7-days	
TM.1	0.5	5.0	30	20	50	152	5500	Very Coarse
2			30	25	45	149	4550	Harsh Mix
3			31	25	44	149	4700	Fair
4			32	28	40	151	5200	Harsh Mix
5			35	27	38	150	5100	Fair
6			38	27	35	149	5150	Fair
7			35	30	35	150	5650	Satisfactory
8	0.5	4.0	30	25	45	149	5250	Wet Mix
9			35	27	38	148	5300	Fairly Good
10			35	30	35	148	5250	Satisfactory
11			30	26	44	147	5000	Harsh Mix
12			35	31	34	148	5200	Satisfactory
13			33	27	40	149	4450	Fairly Good
14			40	25	35	148	5250	Over-Sanded
15			30	30	40	148	4100	Very Good

TABLE 7 - RESULTS OF PRELIMINARY TESTS

MIX PARTICULARS - Aggregate Proportions (By Weight):-
Sand: ⅜"Agg.: ¾"Agg.: = 30%: 30%: 40%,
Total Surface Area of Aggregates = 832

MIX DETAILS			WORKABILITY		DENSITY (Lb./Cu.ft.)			COMPRESSIVE STRENGTH (Lb./Sq.in.)		
REF. No.	W/C Ratio	A/C Ratio	Slump ins	Comp. Factor	3-days	7-days	28-days	3-days	7-days	28-days
P.1	0.4	3.0	1¼	0.94	152	152	152	7150	9150	10350
2		3.5	¾	.91	153	153	153	7350	9250	10900
3		4.0	0	.84	154	154	154	7550	9350	11800
4	.5	3.0	X	.99	147	148	148	4350	6000	7700
5		3.5	X	.97	151	151	151	4950	6650	8150
6		4.0	3	.95	149	149	150	5100	6800	8800
7		5.0	1¼	.89	149	149	150	5500	7000	8950
8		6.0	¾	.85	152	152	152	6000	7550	9100
9		7.0	0	.81	152	152	153	6100	7700	9200
10	.6	5.0	3	.95	150	151	151	3300	4500	6400
11		6.0	¼	.90	150	150	151	3850	5000	7000
12		6.5	0	.89	150	152	152	4150	5350	7350
13	.7	5.5	X	.96	148	149	149	2500	3300	4500
14		6.0	2¼	.95	150	150	150	2850	3750	4900
15		7.0	¼	.92	150	150	150	3000	4050	5300
16	.8	7.0	4½	.95	148	148	148	2650	3250	4050
17		7.5	1	.93	148	148	148	2800	3500	4200
18		8.0	¾	.92	149	149	150	2900	3550	4350

NOTE: 'X' Indicates Collapsed Slumps

TABLE 8(A) - RESULTS OF MAIN TESTS -(1ST TESTS)
A-SERIES TESTS - FOR GRADING NO.1.

MIX PARTICULARS - Aggregate Proportions (By Weight):-
Sand: $\frac{3}{8}$"Agg.: $\frac{3}{4}$"Agg.: =22½%: 22½%: 55%.
Total Surface Area of Aggregates = 641

MIX DETAILS			COMP-ACT-ING FACTOR	DENSITY (Lb./Cu.ft.)			COMPRESSIVE STRENGTH (Lb./Sq.in.)		
REF. No.	W/C Ratio	A/C Ratio		3 days	7 days	28 days	3 days	7 days	28 days
A.1	0.30	3.0	0.786	157	157	157	9920	11880	14600
2	.35	3.0	.898	154	155	155	7810	10210	11400
3		4.5	.795	157	158	158	8040	10670	12370
4	.40	3.0	.962	153	153	154	5330	7740	9940
5		4.5	.885	155	155	155	5900	4360	10810
6	.45	4.5	.899	154	154	155	4350	6310	8840
7		6.0	.827	157	157	157	5600	6730	8960
8	.50	4.5	.926	153	153	154	4060	5560	7330
9		6.0	.884	155	155	155	4480	5810	7790
10	.55	4.5	.947	152	152	153	2670	3750	5520
11		6.0	.900	154	154	154	3230	4540	6270
12		7.5	.856	155	155	155	3940	4790	6040
13	.60	6.0	.926	153	153	153	3230	4540	6290
14		7.5	.870	152	152	153	4190	4960	5830
15	.70	6.0	.946	151	152	152	2540	3190	4380
16		7.5	.909	152	153	153	2940	4170	5060
17		9.0	.871	149	149	149	2250	2880	4020
18	.80	7.5	.928	151	151	151	2150	2810	3580
19		9.0	.914	151	152	152	2480	2790	4170
20	.90	7.5	.948	150	150	150	2020	2500	3210
21		9.0	.927	151	151	151	2000	2460	3440

TABLE 8(B) - RESULTS OF MAIN TESTS -(1ST TESTS)
B-SERIES TESTS - FOR GRADING NO.2.

MIX PARTICULARS - Aggregate Proportions (By Weight);-
Sand: $\frac{3}{8}$"Agg.: $\frac{3}{4}$"Agg.: = 30%:25%:45%
Total Surface Area of Aggregates = 827.

MIX DETAILS			COMP-ACT-ING FACTOR	DENSITY (Lb./Cu.ft.)			COMPRESSIVE STRENGTH (Lb./Sq.in.)		
REF. No.	W/C Ratio	A/C Ratio		3 days	7 days	28 days	3 days	7 days	28 days
B.1	0.30	3.0	0.785	156	156	156	8060	10430	12630
2	.35	3.0	.897	155	155	155	6910	9350	11230
3		4.5	.803	157	157	158	7100	9440	11330
4	.40	3.0	.968	153	153	153	5380	7210	10310
5		4.5	.856	156	156	156	6060	8170	10830
6	.45	4.5	.918	154	154	155	4830	6080	8740
7		6.0	.848	157	157	157	5000	6290	8600
8	.50	4.5	.943	153	153	154	3910	5480	7610
9		6.0	.866	155	155	155	4500	5580	7540
10	.55	4.5	.956	151	152	152	2960	4080	5540
11		6.0	.902	154	154	155	3690	4790	6520
12		7.5	.850	154	154	154	3800	5210	6030
13	.60	6.0	.921	153	153	154	3210	3990	5650
14		7.5	.863	153	153	154	3380	4150	5750
15	.70	6.0	.948	152	152	153	2600	3150	4500
16		7.5	.910	152	152	153	2690	3310	4570
17		9.0	.854	151	151	152	2860	3410	4790
18	.80	7.5	.924	149	150	150	2290	2650	3170
19		9.0	.898	151	151	151	2270	3000	3670
20	.90	7.5	.940	148	148	149	1790	2120	2880
21		9.0	.912	151	151	151	1960	2480	3040

TABLE 8(C) - RESULTS OF MAIN TESTS - 1ST TESTS
C-SERIES TESTS - FOR GRADING NO.3.

MIX PARTICULARS - Aggregate Proportions (By Weight),
Sand: $\frac{3}{8}$"Agg: $\frac{3}{4}$"Agg: = 43%: 22%: 35%.
Total Surface Area of Aggregates
= 1111

MIX DETAILS			COMP-ACT-ING FACTOR	DENSITY (Lb./Cu.ft.)			COMPRESSIVE STRENGTH (Lb./Sq.in.)		
REF. No.	W/C Ratio	A/C Ratio		3 days	7 days	28 days	3 days	7 days	28 days
C.1	0.30	3.0	0.788	155	155	155	8500	10370	13080
2	.35	3.0	.848	153	154	154	7920	9810	11000
3		4.5	.809	153	153	153	6560	8600	10420
4	.40	3.0	.944	152	152	152	6460	8750	10700
5		4.5	.844	152	153	154	7000	9130	10350
6	.45	3.0	.982	149	149	150	5540	7560	9360
7		4.5	.877	152	152	152	5460	7380	9190
8		6.0	.836	151	151	151	5580	7480	9020
9	.50	3.0	.991	148	148	148	4130	5810	7900
10		4.5	.930	150	150	150	4330	6000	7660
11		6.0	.862	151	151	151	4460	5980	7180
12	.55	4.5	.967	151	152	152	2540	3750	5540
13		6.0	.886	152	152	152	3710	4410	6250
14		7.5	.850	149	149	149	3830	5310	6000
15	.60	4.5	.973	148	148	149	3460	4540	6250
16		6.0	.901	148	149	149	3270	4040	5370
17		7.5	.860	148	148	148	3080	3760	5130
18	.70	6.0	.938	149	149	149	2830	3540	4830
19		7.5	.885	145	145	145	2720	3170	4060
20		9.0	.855	148	148	149	2710	3290	4250
21	.80	6.0	.968	148	148	148	2380	3000	4060
22		7.5	.909	147	147	147	2190	2790	3430
23		9.0	.867	146	147	147	1900	2590	3130
24	.90	7.5	.938	148	148	148	1750	2380	3170
25		9.0	.875	144	144	144	1600	2290	2730
26	1.00	7.5	.967	147	147	147	1620	2130	2690
27		9.0	.920	146	146	146	1460	1980	2500

TABLE 8(X) - RESULTS OF MAIN TESTS - (1ST TESTS)
RESULTS FOR 6"CUBE SPECIMENS

MIX DETAILS			COMPACTING FACTOR for Grading Nos.:-			DENSITY (Lb./Cu.ft.) at 28 days for Grading Nos.:-			COMPRESSIVE STRENGTH at 28 days,(lb./Sq.in) for Grading Nos.:-		
REF. No.	W/C Ratio	A/C Ratio	1	2	3	1	2	3	1	2	3
22	0.50	4.5	0.926	0.943	0.930	153	152	150	6950	7020	7730
23		6.0	.884	.866	.862	154	154	150	7230	1730	6870
24	.55	4.5	-	-	.967	-	-	150	-	-	5430
25	.60	6.0	-	.921	.901	-	152	149	-	5300	5250
26		7.5	.870	-	-	153	-	-	5450	-	-
27	.80	7.5	-	.920	-	-	152	-	-	2930	-
28	.90	7.5	.948	-	-	151	-	-	2810	-	-

TABLE 9 - RESULTS OF CHECK MIXES - (2ND TESTS).

MIX DETAILS			DENSITY (Lb./Cu.ft.) at 28 days for Grading Nos.:			COMPRESSIVE STRENGTH (Lb./Sq.in.) at 28 days for Grading Nos.:		
REF. No.	W/C Ratio	A/C Ratio	1	2	3	1	2	3
1	0.40	3.0	154	153	152	9020	10210	9940
			(154)	(153)	(152)	(10000)	(10620)	(12500)
2		4.5	156	156	154	10170	10380	10190
			(156)	(156)	(154)	(11500)	(11750)	(12500)
3	.50	4.5	153	-	-	6250	-	-
4		6.0	157	-	-	6880	-	-
5	.55	4.5	154	154	151	5830	5910	6670
6		6.0	156	155	153	6130	7140	6770
7		6.0	156*	154*	152*	6130*	6250*	6050*
		6.0	-	(154)	(152)	-	(7060)	(7130)
8		7.5	156	156	152	6500	7730	7020
9	.60	6.0	155	-	-	5540	-	-
10		7.5	154	-	-	4920	-	-
11	.70	6.0	154	153	150	3920	3880	4020
12		7.5	154	153	151	4210	4120	4420
13		9.0	155	155	150	4380	4500	4660
14	.80	7.5	153	153	150	2960	3380	3380
15		9.0	154	153	151	3540	3750	3210
16	.90	7.5	-	153	152	-	2690	2730
17		9.0	-	152	151	-	2600	2710

NOTE: (a) 12 Weeks' Results are shown in Brackets.
(b) '*' Indicates Results from the same Consignment of Cement.

TABLE 10 - RESULTS OF CHECK MIXES - (3RD TESTS)

MIX DETAILS			DENSITY (Lb./Cu.ft.)		COMPRESSIVE STRENGTH (Lb./Sq.in.)	
REF. No.	W/C Ratio	A/C Ratio	3-days	7-days	3-days	7-days
1	0.35	3.0	154	154	7460	9380
2	.40	3.0	150	150	5750	7630
3		4.5	152	152	6420	8290
4	.50	4.5	151	151	4030	5130
5		6.0	151	152	4670	5830
6	.55	4.5	152	152	3460	4460
7		6.0	152	152	3830	4940'c'
8		6.0	154	154	4170	5080'b'
9		6.0	155	155	3750	4710'a'
10		7.5	151	152	4040	5220
11	.60	6.0	151	151	2890	3960
12		7.5	150	151	3500	4330
13	.75	6.0	150	150	2540	3120
14		7.5	151	151	2670	3210
15		9.0	148	149	2600	3130
16	.90	7.5	151	151	2000	2440
17		9.0	147	147	1790	1960

NOTE: Results Obtained Using the same Consignment of Cement are indicated by 'a' for Grading No.1;
'b' ,, ,, ,, 2;
'c' ,, ,, ,, 3.

TABLE 11 - RESULTS OF CHECK MIXES - (4TH TESTS)

MIX DETAILS			DENSITY (Lb./Cu.ft.) at 28 days for Grading Nos			COMPRESSIVE STRENGTH (Lb./Sq.in.) at 28 days for Grading Nos.:		
REF. No.	W/C Ratio	A/C Ratio	1	2	3	1	2	3
1	0.40	3.0	154	152	152	8960	9540	9500
2		4.5	156	156	154	9810	10110	10200
3	.55	4.5	154	153	152	5710	6040	6460
4		6.0	154	154	153	6400	6250	6580
5		7.5	156	154	152	7000	7000	6420
6	.70	6.0	154	153	153	4150	4400	4350
7		7.5	155	154	151	4370	4500	4000
8		9.0	149	154	154	3790	4520	4790
9	.90	7.5	152	152	150	2960	3080	2580
10		9.0	154	153	147	3290	3190	1620

TABLE 12 - RESULTS OF CHECK MIXES - (5TH TESTS)

MIX DETAILS			GRADING No.	COMPACTING FACTOR	DENSITY (Lb./Cu.ft.) at age of:		COMPRESSIVE STRENGTH (Lb./Sq.in.) at age of:	
REF	W/C Ratio	W/C Ratio			7-days	28-days	7-days	28-days
LOW WORKABILITY	0.35	3.6	1	0.835	156	156	9250	12350
		3.5	2	.891	155	155	8670	11350
		3.0	3	.919	152	153	8670	10540
	.45	5.7	1	.867	156	157	5960	8230
		5.9	2	.856	155	155	6130	8250
		5.8	3	.839	151	152	5500	7600
	.55	7.6	1	.847	154	154	4380	5980
		7.5	2	.856	153	153	4330	5810
		7.4	3	.856	150	150	4010	5210
HIGH WORKABILITY	0.40	3.1	1	0.961	154	154	6460	9080
		3.1	2	.978	153	153	5710	9540
		2.9	3	.983	151	152	6790	9830
	.55	4.5	1	.943	155	155	3750	5250
		4.6	2	.956	155	155	4150	5690
		4.7	3	.958	153	153	3920	5690
	.70	6.0	1	.931	153	153	2880	6500
		6.0	2	.948	154	154	3120	4170
		6.1	3	.941	151	151	3060	3750

5. ANALYSIS OF TEST RESULTS

The results obtained were analysed so as to compile data that could be used for concrete mix design. The tabulated results have been represented graphically to enable the effects of the variables on the concrete properties to be clearly seen.

5.1. THE COMPRESSIVE STRENGTH

(i) The Relationship between Compressive Strength and Water/Cement ratio for different Workabilities:

Figures 4(A) to 4(C) have been plotted from the results tabulated in Tables 8(A) to 8(C), to show how the cube strengths at ages of 3, 7 and 28 days vary with the water/cement ratios for mixes of three different degrees of workability. Figures 4(A), 4(B) and 4(C) will be used for mixes corresponding to aggregate grading Nos. 1, 2, and 3 respectively.

Both the water/cement ratio and aggregate/cement ratio quoted are ratios by weight. The experimental values were adjusted slightly so that smooth families of curves could be obtained. The three degrees of workability chosen represent compacting factor values used in Road Note No.4.

(ii) The Relationship between Compressive Strength and Water/Cement ratio for various Aggregate/ Cement ratios:

Figures 5(A) to 5(C) were plotted also from the results given in Tables 8(A) to 8(C). The figures show the variation of cube strength at ages of 3, 7 and 28 days with water/cement ratio for mixes of various aggregate/cement ratios. Figures 5(A), 5(B) and 5(C) will be used for grading Nos.1,2 and 3 respectively.

5.2. THE WORKABILITY

(i) The Relationship between Workability and Water/Cement ratio for various Aggregate/ Cement ratios.

Table 14 is obtained by collecting together the workability results from Tables 8(A) to 8(C). The Table gives the compacting factor values obtained with different combinations of water/cement ratio and aggregate/cement ratio using aggregates corresponding to grading Nos. 1,2 and 3.

Figures 6(A) to 6(C) have been drawn from data taken from Table 14. The figures show the aggregate/cement ratios required to give different compacting factor values at given water/cement ratios for grading Nos.1 to 3 respectively.

(ii) The Relationship between Aggregate/Cement Ratio and Water/Cement ratio for different Workabilities.

Figures 7(A) to 7(C) show the three degrees of workability obtained for different aggregate/cement ratio and water/cement ratio combinations using aggregate grading Nos. 1 to 3. The Figures were plotted from the results tabulated in Table 14. The results plotted in Figures 7(A) to 7(C) are collected together and expressed in tabular form in Table 15. The Table gives the aggregate/cement ratio required to produce three degrees of workability for various water/cement ratios at different aggregate gradings.

This is a mix design Table corresponding to those given in Table 3 of Road Note No.4.

(iii) The Effect of Aggregate Gradings on Workability:

The variation of workability for different aggregate gradings is represented in Figure 8. The Figure shows how the workability varies with various water/cement ratio and aggregate/cement ratio combinations for the three aggregate gradings observed in this investigation. The Figure was also plotted from the information given in Table 14.

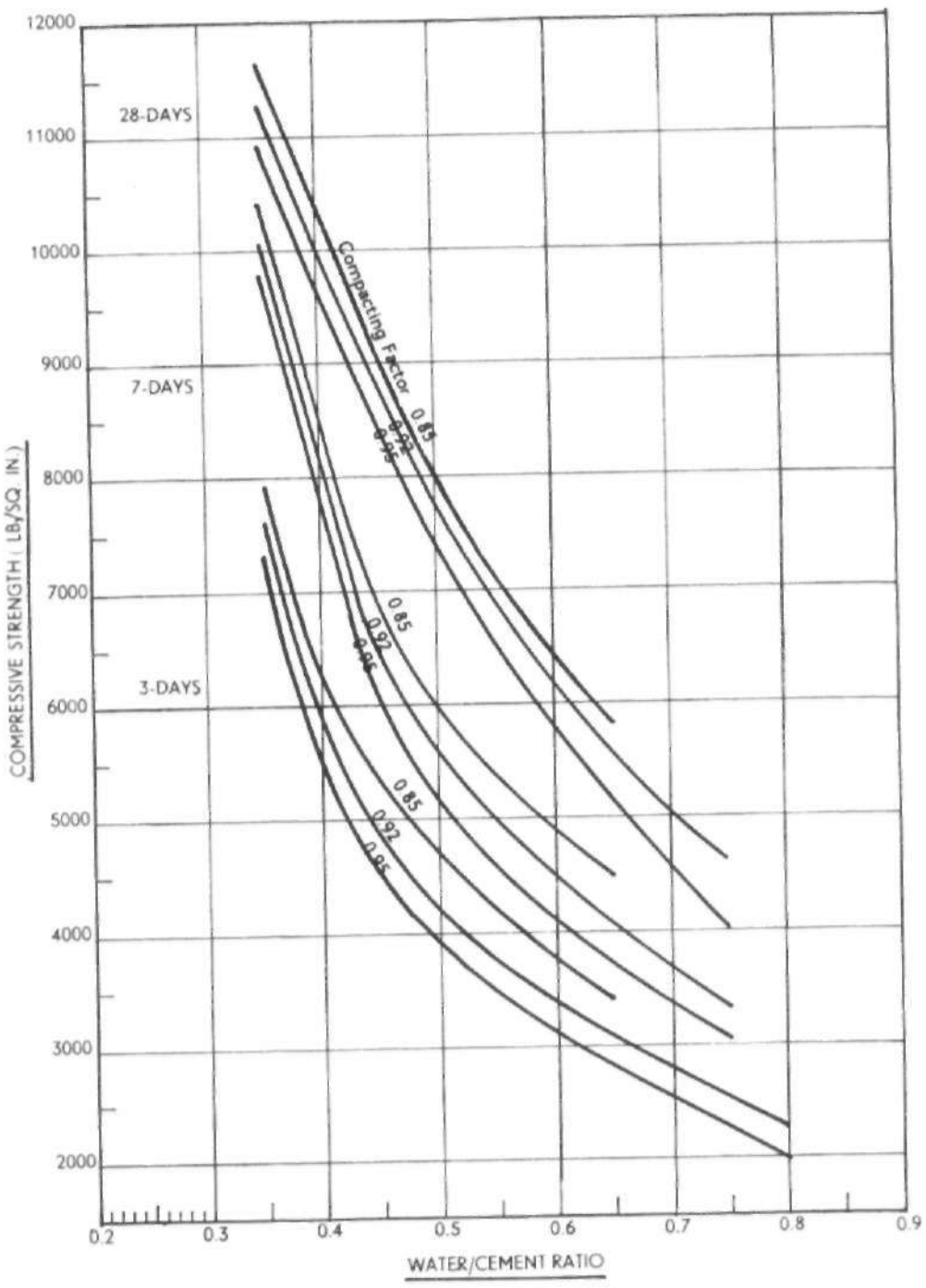


FIGURE 4(A)- RELATIONSHIP OF STRENGTH AT DIFFERENT AGES AND WATER/CEMENT RATIO FOR VARIOUS WORKABILITIES FOR GRADING NO. 1

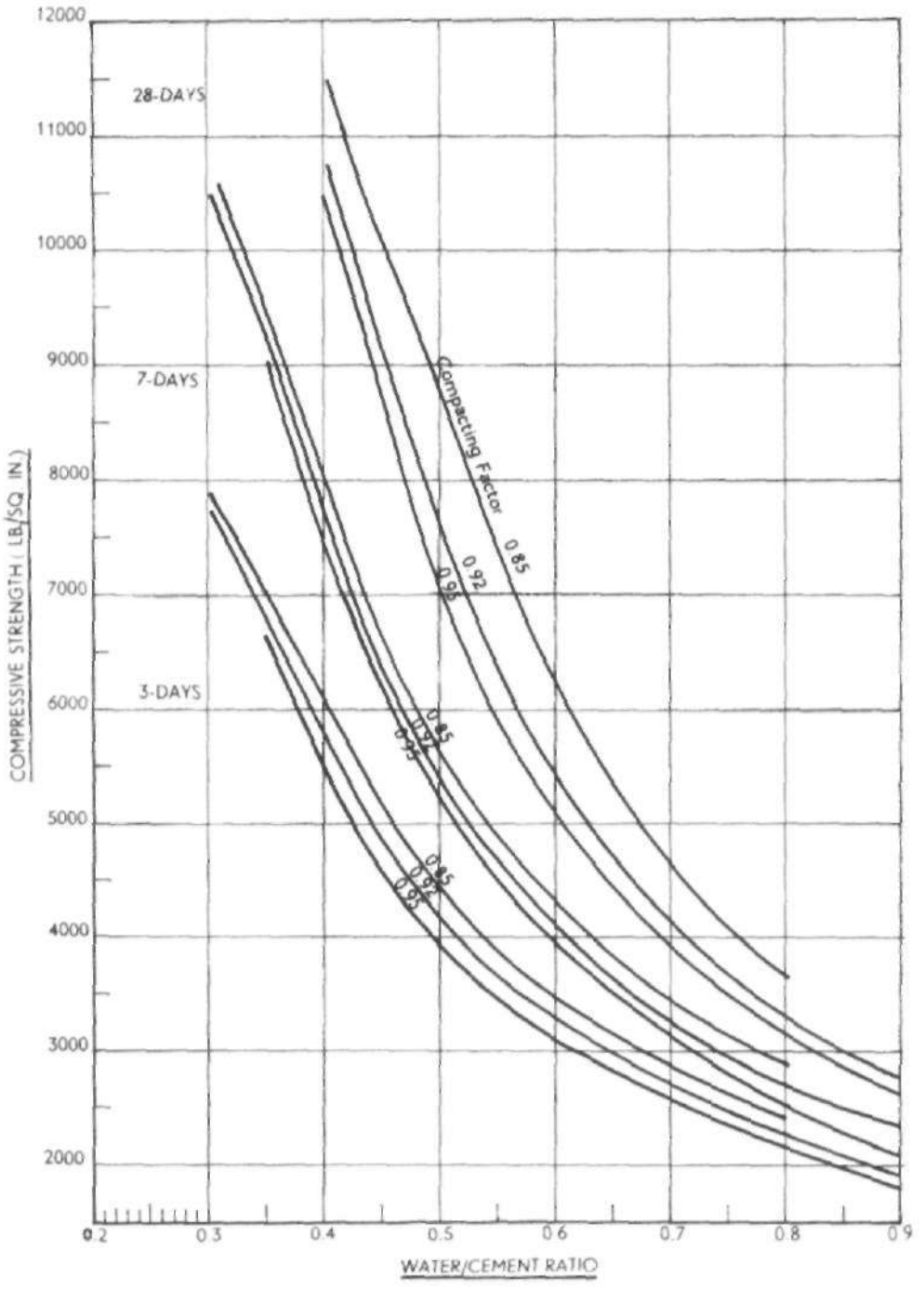


FIGURE 4(B)- RELATIONSHIP OF STRENGTH AT DIFFERENT AGES AND WATER/CEMENT RATIO FOR VARIOUS WORKABILITIES FOR GRADING NO. 2

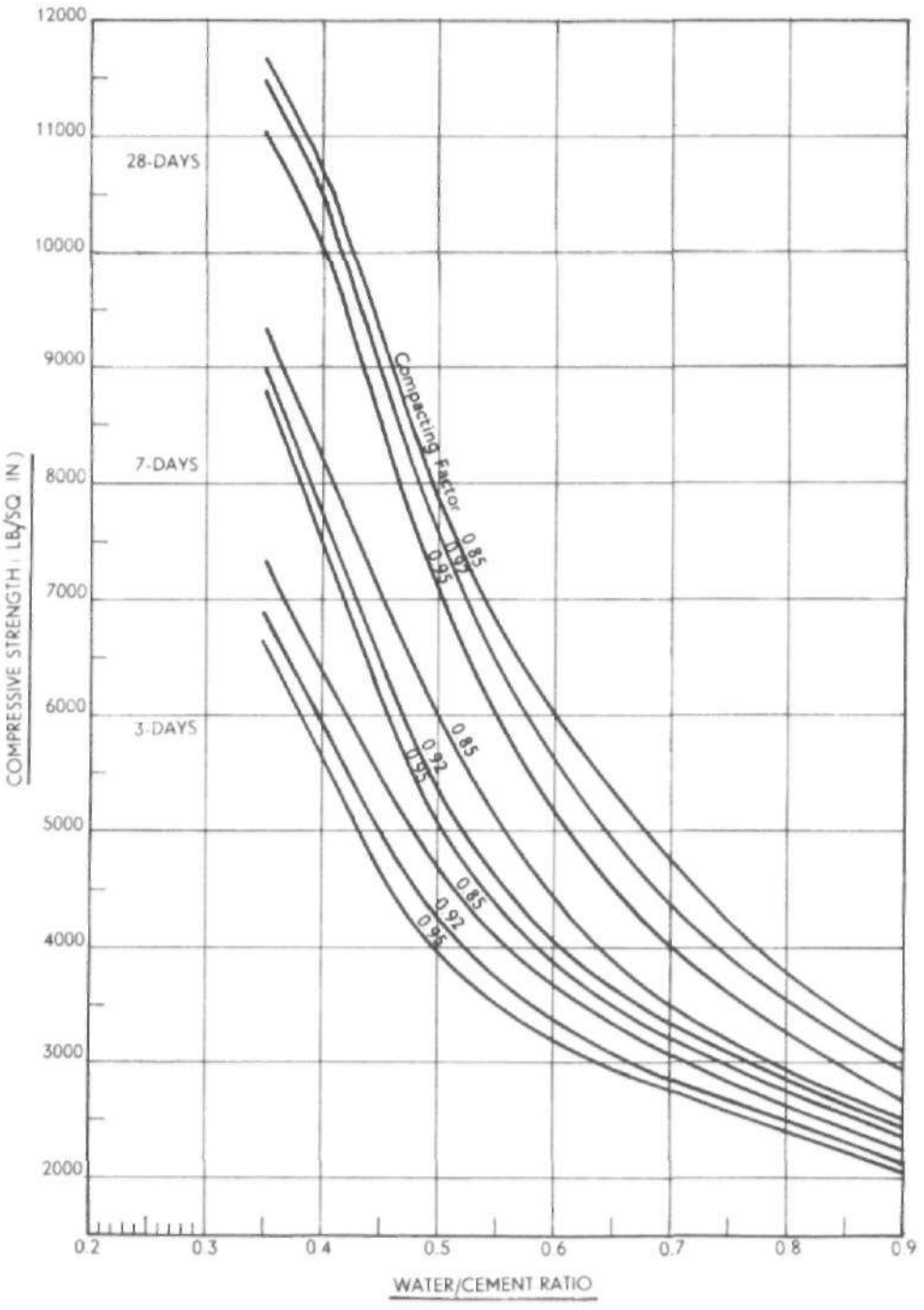


FIGURE 4(C)- RELATIONSHIP OF STRENGTH AT DIFFERENT AGES AND WATER/CEMENT RATIO FOR VARIOUS WORKABILITIES FOR GRADING NO 3

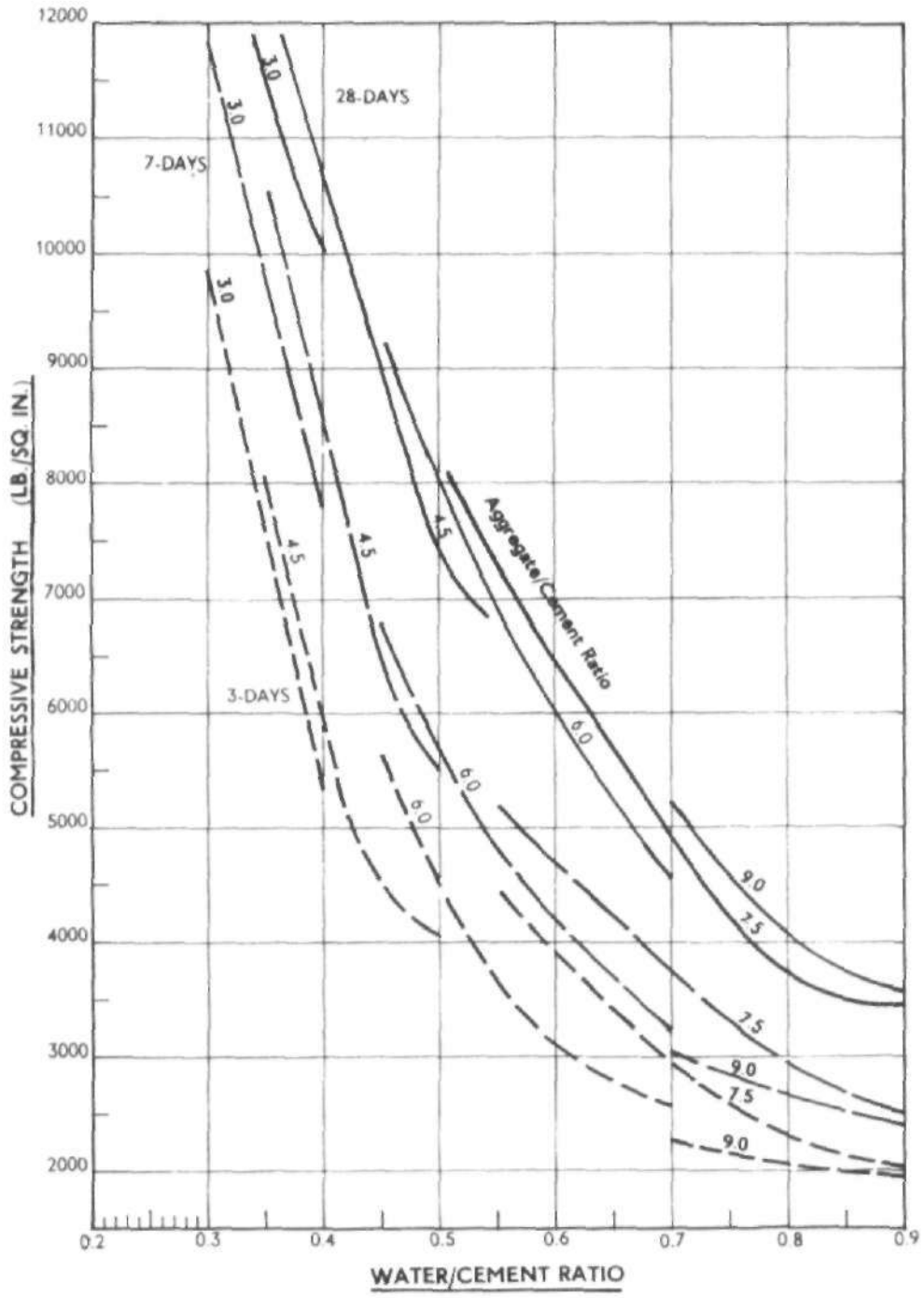


FIGURE 5(A) - RELATIONSHIP OF STRENGTH AT DIFFERENT AGES AND WATER/CEMENT RATIO FOR VARIOUS AGGREGATE/CEMENT RATIOS FOR GRADING NO. 1

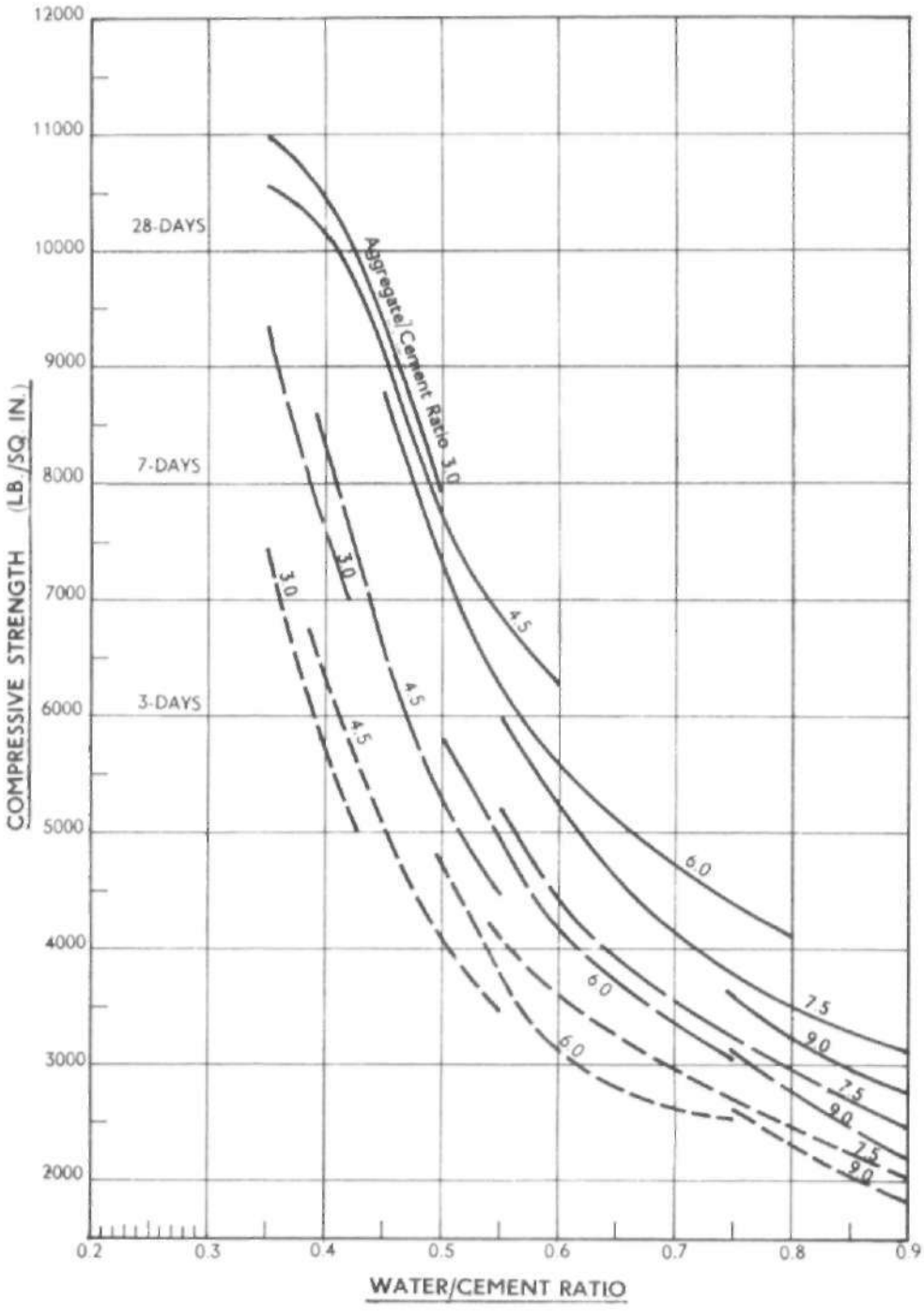


FIGURE 5(C)- RELATIONSHIP OF STRENGTH AT DIFFERENT AGES AND WATER/CEMENT RATIO FOR VARIOUS AGGREGATE/CEMENT RATIOS FOR GRADING NO. 3

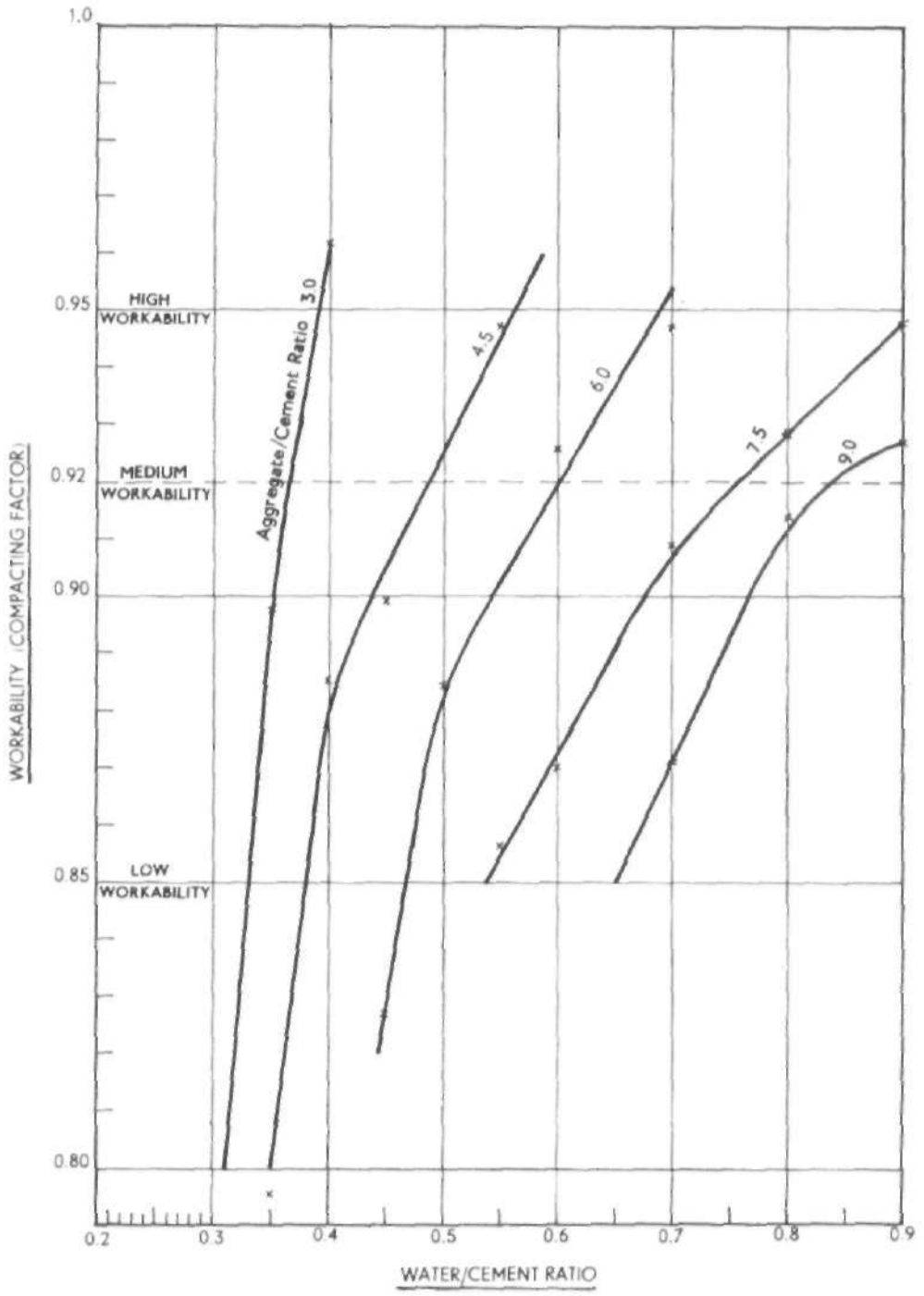


FIGURE 6(A)- RELATIONSHIP OF WORKABILITY AND WATER/CEMENT RATIO FOR VARIOUS AGGREGATE/CEMENT RATIOS FOR GRADING NO. 1

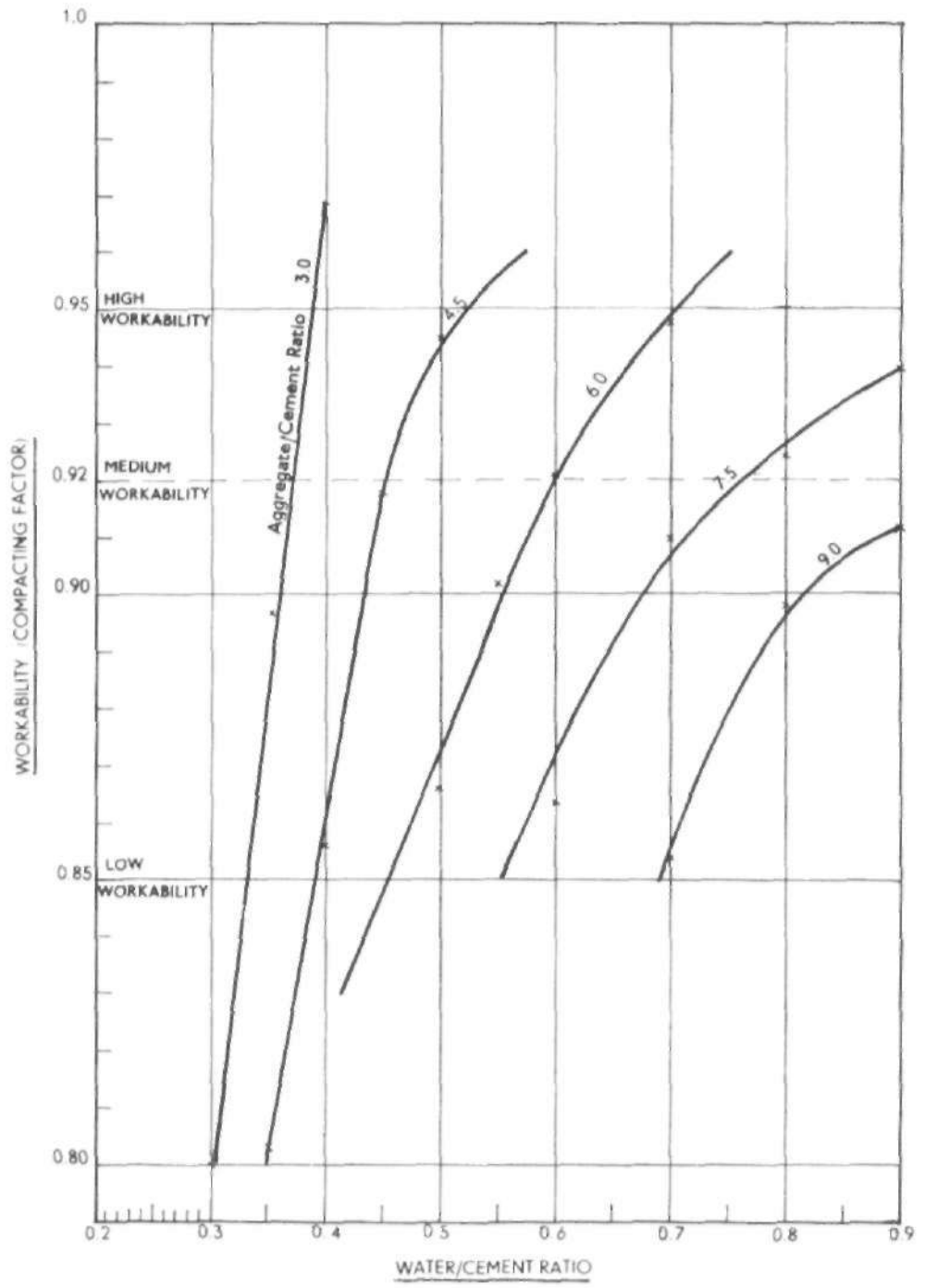


FIGURE 6(B)- RELATIONSHIP OF WORKABILITY AND WATER/CEMENT RATIO FOR VARIOUS AGGREGATE/CEMENT RATIOS FOR GRADING NO 2

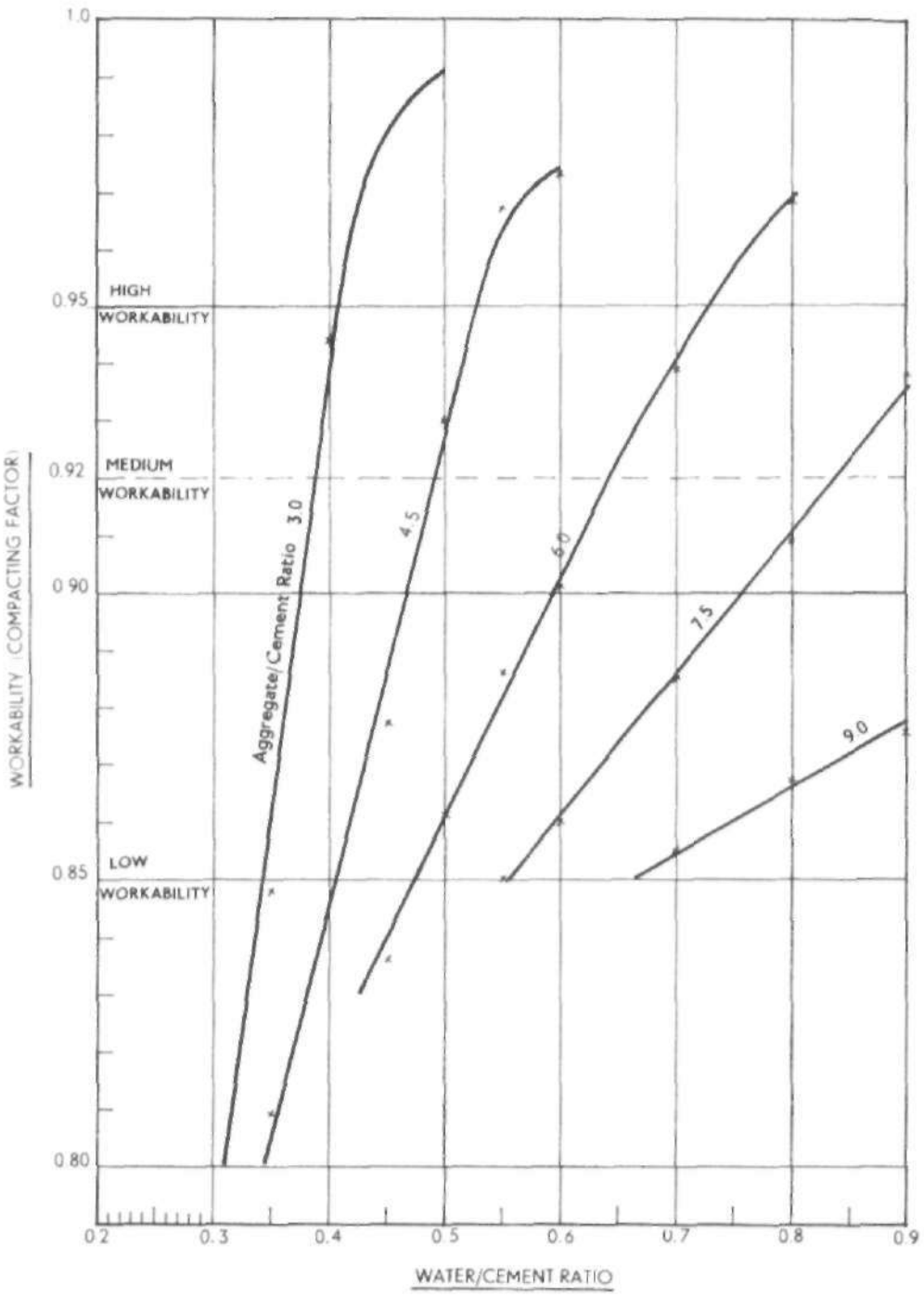


FIGURE 6(C)- RELATIONSHIP OF WORKABILITY AND WATER/CEMENT RATIO FOR VARIOUS AGGREGATE/CEMENT RATIOS FOR GRADING NO. 3

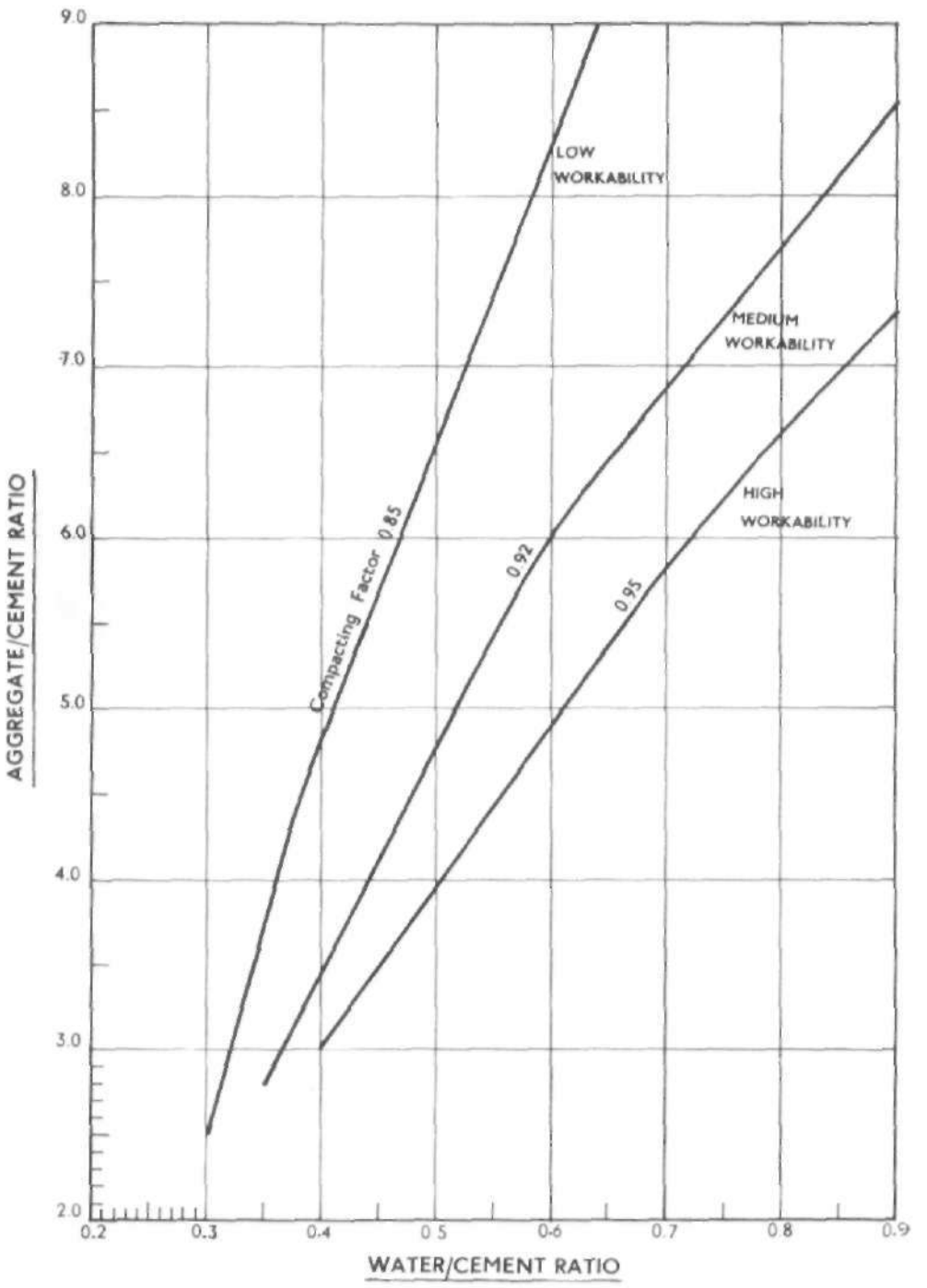


FIGURE 7(A)- RELATIONSHIP OF AGGREGATE/CEMENT RATIO AND WATER/CEMENT RATIO FOR VARIOUS WORKABILITIES FOR GRADING NO. 1

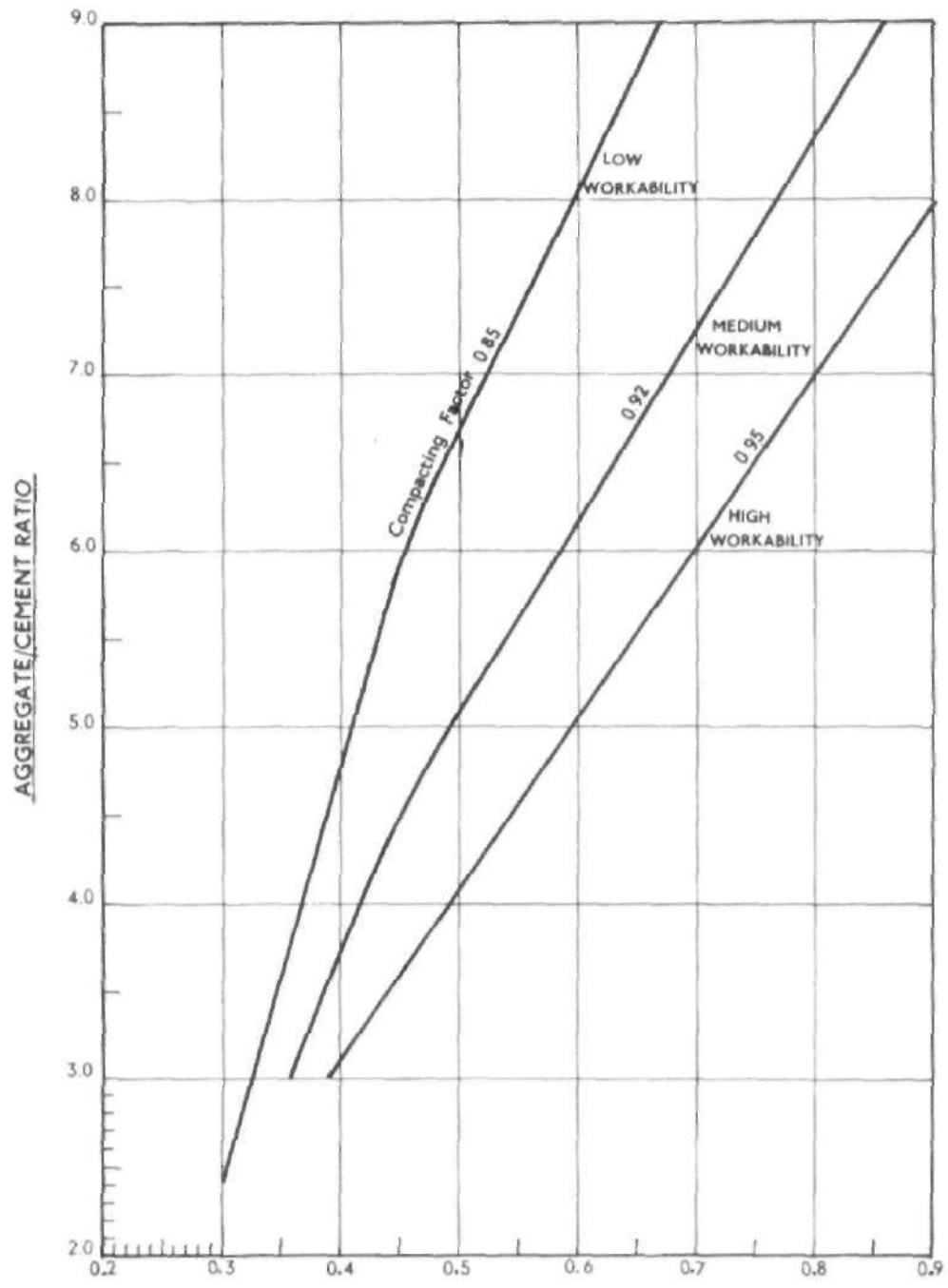


FIGURE 7(B)- RELATIONSHIP OF AGGREGATE/CEMENT RATIO AND WATER/CEMENT RATIO FOR VARIOUS WORKABILITIES FOR GRADING NO. 2

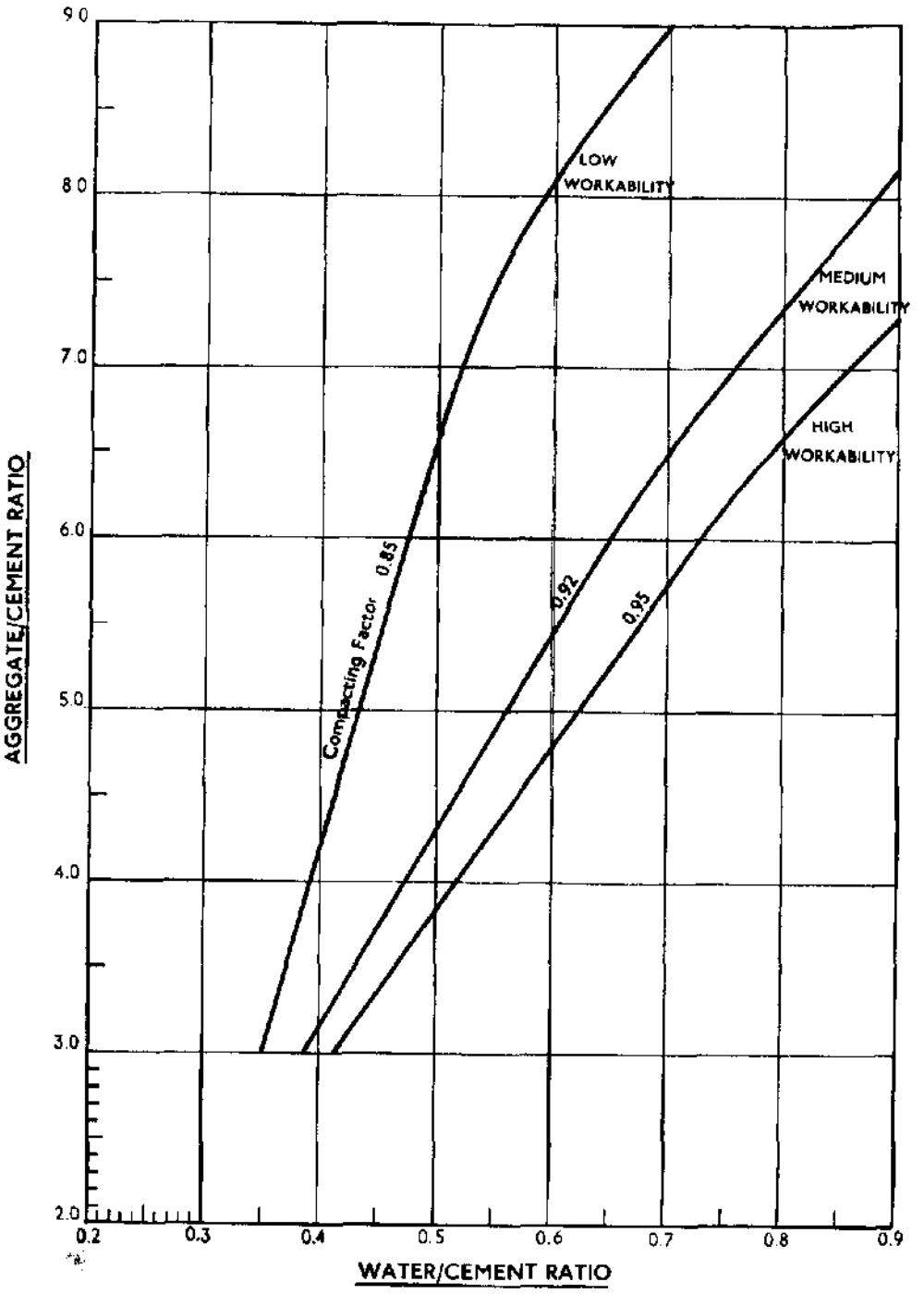


FIGURE 7(C)- RELATIONSHIP OF AGGREGATE/CEMENT RATIO AND WATER/CEMENT RATIO FOR VARIOUS WORKABILITIES FOR GRADING NO. 3

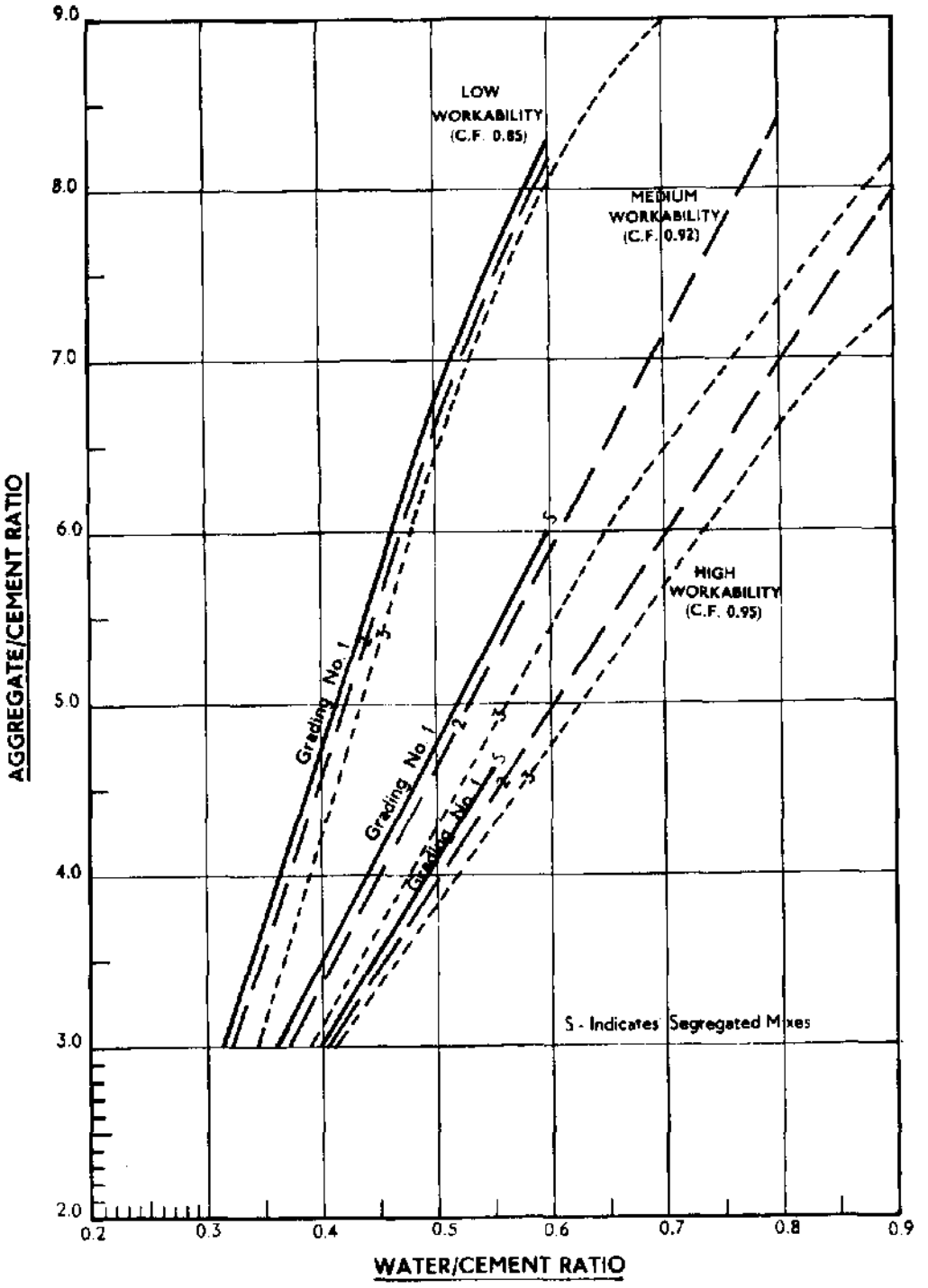


FIGURE 8- VARIATION OF WORKABILITY FOR DIFFERENT AGGREGATE GRADINGS

TABLE 14 - COMPACTING FACTOR VALUES FOR VARIOUS WATER/CEMENT RATIO AND AGGREGATE/CEMENT RATIO COMBINATIONS AT THREE DIFFERENT AGGREGATE GRADINGS.

AGGREGATE/CEMENT RATIOS:		3.0			4.5			6.0			7.5			9.0		
GRADING Nos.:		1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
WATER/CEMENT RATIO (By Weight	0.30	.79	.79	.78												
	.35	.89	.89	.85	.80	.80	.80									
	.40	.96	.96	.94	.88	.86	.84									
	.45			.98	.91	.91	.88	.84	.84	.84						
	.50				.93S	.94	.92	.88	.87	.86						
	.55				.94S	.96	.96	.90	.90	.88	.85	.85	.85			
	.60						.97	.92S	.92	.90	.87	.87	.86			
	.70							.95S	.95	.94	.91S	.91	.89	.87	.85	.85
	.80									.97	.92S	.92	.91	.91S	.90	.87
	.90										.93S	.94S	.94	.93S	.91S	.88

NOTE: 'S' Indicates Segregated Mixes

TABLE 15 - AGGREGATE/CEMENT RATIO REQUIRED TO GIVE THREE DEGREES OF WORKABILITY FOR VARIOUS WATER/CEMENT RATIOS AT THREE DIFFERENT AGGREGATE GRADINGS.

DEGREE OF WORKABILITY		AGGREGATE/CEMENT RATIO (By Weight)								
		LOW (C.F.:0.85)			MEDIUM (C.F.:0.92)			HIGH (C.F.:0.95)		
GRADINGS Nos		1	2	3	1	2	3	1	2	3
WATER/CEMENT RATIO (By Weight)	0.35	3.7	3.6	3.1	2.8	2.7	2.6			
	.40	4.7	4.6	4.2	3.5	3.4	3.1	3.0	3.0	2.9
	.45	5.7	5.6	5.4	4.2	4.0	3.7	3.6	3.5	3.4
	.50	6.7	6.6	6.5	4.8	4.7	4.3	4.1	4.0	3.8
	.55	7.6	7.5	7.4	5.4	5.3	4.9	4.6	4.5	4.3
	.60	8.3	8.2	8.1	6.0	5.9	5.4	S*	5.0	4.8
	.70			9.0	S*	7.2	6.5		6.0	5.7
	.80					8.4	7.3		7.0	6.6
	.90						8.2		8.0	7.3

S* Indicates Segregated Mixes

6. DISCUSSIONS AND COMMENTS ON TESTS RESULTS

6.1. GENERAL DISCUSSIONS

6.1.1. - THE AGGREGATE GRADINGS

The term "grading" is commonly used to describe the distribution of the particles of each size in the aggregate. It is usually represented by means of a curve showing the percentage of the total material passing any given sieve plotted against the sieve size (21). The grading of aggregates may also be specified by means of the specific surface of the combined aggregates (22).

The two methods of grading have been used in this investigation. The aggregates are combined into three separate gradings. The grading curves of the combined aggregates are shown in Figure 1, and the total surface area values are given in Table 5. The three gradings chosen have approximately the same total specific surface area as those gradings given in Road Note No 4 even though their grading curves are somewhat different.

Figure 1 shows that the fine aggregate used is within a zone 2 grading as classified in B.S. 882;

but the sand appears to have a slightly higher percentage in the finer fractions. The gradings of this available fine aggregate are of a type that makes it impossible to combine them with the available two sized coarse aggregates to obtain an overall grading curve similar to those in Road Note No. 4. The closest combination is achieved by matching curve No. 2. Grading No. 1 of this investigation is similar to curve No. 1 of Road Note No 4 but the percentage of particles passing sieve No 3/16-in. is much lower in this investigation than in the case of Road Note No. 4's curve No. 1. Grading No 3, which is the highly sanded mix in this investigation, falls in between curve Nos. 3 and 4 in the coarse particles of the sand, but the finer materials passing a No. 25 sieve, fall in between curve Nos. 2 and 3 of Road Note No. 4.

Total Specific Surface Area of Combined Aggregates:

It is generally believed that, all other things being equal, aggregates of the same total specific surface area will produce concrete mixes of identical workability irrespective of the gradings of the aggregates; and that workability is a function of the specific surface of the combined aggregates [22]. Hence, for a given water/cement ratio and aggregate/cement ratio the

workability of the mixes will be similar provided the total specific surface of the aggregates is the same. An increase in specific surface causes a reduction in workability for a given water content of the mix. This is attributed to the fact that there will be more surfaces of particles to coat by the available free water in the mix. The effect of specific surface of combined aggregates on compressive strength is not significant, an increase in the surface area only causes slight reduction in the strength.

The specific surface is defined as the ratio of the total surface area of the particles to the gross apparent volume of the materials. For a given size of material, deviation of the particle shape from an ideal sphere increases as the specific surface increases. The surface texture of materials are commonly compared by referring to their specific surfaces.

Because of the difficulty involved in measuring the actual values of the specific surface of aggregates, an arbitrary "surface area index" is commonly adopted, and this is sufficiently accurate for practical purposes (19). The index assumes that there is no change in surface texture of the particles with change in size

and that the surface area index doubles as the material size halves. The surface area value for a particular particle size is obtained by multiplying the percentage of particles retained on that sieve by the appropriate surface area index. Table 5 shows the calculations of the total surface area of the combined aggregates used in this investigation. The total surface area values of the gradings used are very close to the values of the gradings of Road Note No.4.

If the previous concepts on the relationship of the specific surface of aggregates and the workability of concrete are correct, then a mix prepared with an aggregate having the same total surface area as one of the gradings suggested in this investigation, would be expected to have the same workability as those obtained in this report. Hence, the mix design method proposed here is based on this concept.

6.1.2. - THE WORKABILITY OF CONCRETE

The term "workability" is defined as the property of the concrete which determines the amount of useful internal work necessary to produce full compaction (19). The term is used to denote that property of fresh concrete which determines the ease of compaction and the ability of the mix to flow into the mould and around reinforcement; the resistance of the mix to segregation and bleeding during mixing and placing; and the ease with which a smooth surface finish can be obtained on the concrete. These compactability, mobility, stability and finishability characteristics of fresh concrete are essential for the achievement of a satisfactorily compacted and homogeneous concrete (23).

(i) Factors Affecting Workability.

Many factors affect the workability of concrete but the most important ones are:-

(a) the grading, shape of particles, surface texture, maximum size and nature of the aggregates,

(b) the water content,

(c) the cement content,

and(d) the mix proportions.

The effect of aggregate grading is not constant but depends to a certain extent on the cement content and workability of the mix. There is a tendency for smooth rounded aggregates to give greater workability than the coarse angular-shaped ones. Also concrete mixes made with maximum sized aggregate give better workability than the smaller sized ones. Within certain limits, the higher the water/cement ratio, the greater the degree of workability.

(ii) Measurement of Workability.

Workability is a most difficult property to assess quantitatively and so far no perfect test has yet been devised for its measurement. Most of the available tests will measure only one characteristic of workability.

The most well known methods of assessing workability of concrete are the slump test and the compacting factor test. The standardised testing procedure of these tests are fully described in B.S.1881.

The limitations of these tests will be briefly discussed below. Other workability tests include: the Flow Table test, the Kelly Ball test, and the Consistometer tests.

(a) The Slump Test.

The slump test is a simple practical method for maintaining reasonable uniformity in the consistence of concrete produced in the works. The test is an approximate measure for consistence and shear resistance of concrete to flow under its own weight. It measures therefore the mobility and stability characteristics of concrete. The use of the test is limited to concrete of medium and high workability and will not be suitable for either very dry or very wet mixes. Other reasons why the test is not quite suitable are:-

(i) the results of the test are liable to a wide range of random variations.

(ii) concrete of widely different workability may have the same slump value. The test is only reliable in a certain limited range of concrete.

The experience gained in the preliminary tests undertaken in this investigation confirmed the above limitations of this method of workability measurement. A more reliable test which overcomes most of the disadvantages of the slump test is the compacting factor test, and this was the test resorted to in this investigation.

(b) The Compacting Factor Test.

The compacting factor test is a method of test which is claimed [21] to be based directly upon the definition of workability, in that it assesses the degree of compaction obtained by doing a standard amount of work on the concrete. The test measures compactability charateristics of concrete mixes. It is more sensitive to changes in the water/cement ratio of rich mixes than lean mixes, but it is less accurate for dry, harsh mixes with low degree of workability.

Experience with the compacting factor test has shown that reliable results are obtained, which enable useful comparison to be made between the various mixes which in turn agrees closely with visual observations made. The test is widely used for laboratory tests and is mainly applicable to hand-placed concrete.

(iii) The Degrees of Workability

The degree of workability of concrete is normally assessed by giving regard to the class of work and the usage of the concrete, the maximum size of aggregate used, and the conditions and method of placing of the concrete. The three degrees of workability chosen in this investigation have been adopted from published work [8,12], and they give regard to these factors. For example :

a "LOW" degree of workability corresponds with a compacting factor of 0.85, and slump of ½-in. to 1-in.; and is appropriate for use for simply reinforced sections compacted by vibration, and vibrated mass concrete slabs and roads.

a "MEDIUM" degree of workability corresponds with a compacting factor of 0.92 and slump of 1-in. to 2-in.; and is suitable for use for vibrated, heavily-reinforced sections, and manually compacted simply-reinforced sections, slabs and roads.

a "HIGH" degree of workability corresponds with a compacting factor of 0.95 and slump of 2-in. to 5-in.; and is appropriate for congested reinforced concrete sections compacted by hand. It is not normally suitable for vibration.

6.1.3. THE STRENGTH OF CONCRETE.

The strength of concrete is probably the most valuable property which governs its quality and it seems to be a good index for assessing its other properties. Other important characteristics of hardened concrete such as durability and impermeability have been found to have direct connection with the strength of concrete (23).

The strength property of concrete may be described as its ability to resist force, and it is usually taken as the unit force or stress required to produce rupture. This rupture may be caused by the applied compressive stress, that is, the failure due to the crushing force; or the tensile stress, that is, the failure due to splitting or in cohesion; or by shearing stress, that is, the sliding failure. As concrete is a brittle material, its resistance in both tension and in shear is negligible compared with its compressive strength. Hence for purpose of structural design the compressive strength is generally taken as the criterion for the quality of concrete. Also in practice, it is more convenient to measure the crushing strength than the other types of strengths of concrete.

However, there are instances where tensile strength is of interest to engineers such as in concrete for highway pavements, airfield works and in dam construction. Tensile strength is also of importance with regards to cracking and drying shrinkage properties of concrete.

Since the crushing strength is the main kind of strength that interests a concrete mix designer, the present investigation has therefore been limited to this property.

(i) Factors Affecting Concrete Strength.

The following are the main factors influencing compressive strength of concrete[24]:

(a) the type and quality of cement,

(b) the type, size and properties of the aggregates,

(c) the water content,

(d) the mix proportions and the dggree of compaction,

(e) the climatic and curing conditions,

(f) the age or maturity,

(g) the testing methods and conditions.

Most of the above factors are largely governed by economic considerations, and the site engineer often has very little jurisdiction over their variation.

The main factor which is often the responsibility of the engineer is the controlling of the relative proportions of the materials which constitute the concrete; that is, the cement water, air and the aggregate constituents.

It is a long established fact that the compressive strength of concrete for a given type of material and conditions of test depends mainly upon the strength of the cement-paste matrix; that is the cement, water and air constituents, and that the strength of the matrix increases as the ratio of the cement to the water and the air decreases [23,24]. If full compaction is obtained so that practically all the air voids are eliminated, it may be assumed that the strength depends mainly on the ratio of the cement to the water; and this is the basis of the well known Abram's water/cement ratio law which was previously stated. The present investigation applies the same concept in selecting the mix proportions to acquire the desired compressive strength.

(ii) The Water/Cement Ratio.

The term "water/cement ratio" is generally defined as the ratio of the weight of water to the weight of cement in any given mix. There are three main sources from which water may be present in a batch of concrete, namely:

(a) Water added during mixing,

(b) Water held on the surface of the aggregate,

(c) Water absorbed into the aggregate.

The amount of water added when mixing plus the amount of water held on the surface of the aggregate, i.e. water from sources (a) and (b), are termed the 'FREE WATER'. The free water plus the amount of water actually absorbed by the aggregate is referred to as the 'TOTAL WATER'.

When specifying the water/cement ratio of a mix, it is necessary to clarify the water content used as this may either be based on the free water or on the total water. The values of the water/cement ratio used throughout this investigation are the "total water/cement ratio". These are based on the total weight of water actually added to the air-dry materials in

the mixer. Hence allowance has not been made for the absorption of the mixing water by the aggregates to bring them to a saturated surface-dry condition.

This adjustment is considered unnecessary in this investigation because the aggregates used possess very low water absorption property and were in dry condition. The adjustment for absorption of added water by the dry aggregates will normally reduce the amount of water available as "effective water" for hydration and may result in inadequate free water.

In tropical countries, especially in the hot-dry regions as in Northern Nigeria where the aggregates are completely dry most of the year, it seems advisable to use the water/cement ratios based on the total weight of water added to the mix rather than the effective water/cement ratio commonly used in the United Kingdom and other temperate countries where the aggregates are often used in surface-dry state.

However, during the wet seasons in the tropics, it will be advisable to adjust for the surface moisture of the aggregates; and also if porous aggregates are used, allowance must be made for the moisture absorption of the aggregate.

6.1.4. THE DENSITY OF CONCRETE

The term "density" is sometimes referred to as the unit weight of the material. It is the ratio of the weight of the specimen to its volume.

The density of concrete varies with the mix proportions, the character and maximum size of aggregates, and the degree of compaction obtained. The extent of compaction achieved depends mainly on the method used to consolidate the concrete, and this may either be by hand (commonly used on the site on small jobs) or by mechanical vibration,(using vibrating table, immersion vibrators, surface vibrators and form-vibrators.).

The specimens used in this study were compacted by vibration on a vibrating table and care was taken to ensure that the cubes were fully compacted. This was determined by observing the cubes and making sure there were no air bubbles coming out on the top of the cubes The process of compacting concrete on the vibrating table causes the particles of the concrete to be momentarily loosened to allow them to be drawn into a compact mass. This compaction is done by overcoming the internal

friction between the individual particles of the mix and also the surface friction of the boundary surfaces such as the sides of the moulds.

The results obtained in this investigation confirm that aggregate grading affects the concrete density. Grading No.1, which is the coarsest of the three gradings produces concrete with the maximum density. The least density values were obtained with grading No.3. The density results in pounds per cubic foot vary from 149 to 158 for grading No.1, 148 to 157 for grading No.2, and 144 to 155 for grading No.3.

The variables observed in this study exert the same effect on the density as they do on compressive strength. Hence to a certain extent the compressive strength and the density of concrete are inter-related in as much as the water/cement ratio and aggregregate/cement ratio are concerned. For example, for fully compacted concrete, the density of concrete reduces as the water/cement ratio increases, and at a given water/cement ratio the density increases as the aggregate/cement ratio increases.

6.2. DISCUSSIONS ON THE TEST RESULTS

6.2.1. THE RELATIONSHIP BETWEEN COMPRESSIVE STRENGTH WATER/CEMENT RATIO, AND AGGREGATE/CEMENT RATIO:

The variation of cube strength at ages of 3, 7 and 28 days with water/cement ratio for mixes of different workabilities using aggregates corresponding to grading Nos. 1, 2 and 3, has been shown in Figures 4(A), 4(B) and 4(C) respectively.

It can be seen from the figures that for a given workability, an increase in water/cement ratio causes a reduction in compressive strength. This is in agreement with the long established fact of the water/cement ratio and strength relationship.

For a given water/cement ratio, an increase in workability will also cause a reduction in compressive strength. This reduction in strength with an increase in workability may be attributed to the fact that additional cement will be required to produce the increase in the workability. The increase in cement content will produce an increase in water gain which consists of the displacement of water from the mortar matrix. Some of the displaced water will be trapped

under the aggregates and thus reduce the compressive strength of the concrete.

The water/cement ratio necessary to produce the specified compressive strength for any desired workability can be easily determined from Figure Nos. 4(A) to 4(C). Figures 4(A), 4(B) and 4(C) will be used for mixes made from aggregates corresponding to grading Nos. 1, 2 and 3 respectively.

Figures 5(A) to 5(C) show how the cube strengths vary with the water/cement ratio for mixes with various aggregate/cement ratios using aggregates corresponding to grading Nos. 1, 2 and 3. It can be seen from the figures that for a given water/cement ratio an increase in aggregate/cement ratio causes an increase in compressive strength, but for very lean mixes, (at an aggregate/cement ratio of about 9.0) and highly sanded mixes, a reverse effect tends to occur. These figures represent alternative ways of presenting the data given in Figures 4(A) to 4(C). Figures 5(A) to 5(C) may be used to determine the water/cement ratio required to produce a specified compressive strength for any given aggregate/cement ratio.

6.2.2. THE RELATIONSHIP BETWEEN WORKABILITY, WATER/CEMENT RATIO AND AGGREGATE/CEMENT RATIO:

Figures 6(A) to 6(C) indicate the relationship of aggregate/cement ratio with water/cement ratio and compacting factor for the three aggregate gradings and are plotted from Table 14. The variations of workability with various combinations of water/cement ratio and aggregate/cement ratio for grading Nos. 1,2 and 3 are shown in Figures 7(A) 7(B) and 7(C) respectively.

As can be seen from Figures 7(A) to 7(C) or Table 14, at a given water/cement ratio, there is a noticeable reduction in the workability of concrete mixes as the aggregate/cement ratio increases. This reduction is more pronounced with the mixes made using aggregate grading No.3, which is the highest sanded mix. This may be due to the fact that as the sand content of a mix increases there is an increase in the specific surface of the aggregate particles and hence a greater surface to wet by the mixing water and consequently a reduction in the available free water for workability. Also there will be a tendency for slightly greater absorption of the mixing water as the sand content of the mix increases. The compacting factor is relatively more sensitive to variation in the aggregate/cement ratio of richer mixes than in lean mixes.

The variation in compacting factor values is not significant with change in aggregate grading. The compacting factor values for mixes made with grading No.1 and those of No.2 are very close, but there is a noticeable reduction in compacting factor values when grading Nos. 1 and 3 are compared. Grading No.3 which has the highest total surface area value gives the lowest compacting factor values. The variation in compacting factor values is more pronounced in lean mixes.

Grading No.1, which is the coarsest of the three gradings, shows the greatest proneness to segregation. This is due to its very low sand content. The grading will not be suitable for lean mixes with high water content. It will only be advisable for use in rich mixes where high strength is desirable.

Table 15, which is a tabular expression of the results plotted in Figures 7(A) to 7(C) is a useful concrete mix design data. From either the Table or the Figures, the aggregate/cement ratio against a particular water/cement ratio may be estimated for any desired workability at a particular aggregate grading. The procedure to follow in using the data for concrete mix design is described in Section 7 of this report.

6.3. COMMENTS ON THE EFFECTS OF THE VARIABLES ON CONCRETE PROPERTIES.

Most of the results obtained in this investigation confirm the previous concepts on the effects of aggregate grading, water/cement ratio, aggregate/cement ratio, and ages at test, on the properties of concrete. The properties of concrete mainly concerned with in this investigation being the workability and the compressive strength.

The following remarks can be made on the results obtained:-

6.3.1. THE EFFECT OF AGGREGATE GRADING.

(i) WORKABILITY:

Table 14 shows that the highest workability is obtained with a mix corresponding to grading No.1 which is the grading with the lowest sand content and possesses the lowest total specific surface area.

The results are therefore, in agreement with previous concepts that a reduction in total specific surface area causes an increase in workability for a given water/cement ratio. A reduction in fine aggregate content of a mix generally increases the workability of the mix.

That explains why higher compacting factor values are obtained with grading No.1 than with grading No.2 or 3. For a given water/cement ratio and aggregate/ cement ratio, a change in grading from No.1 to 3. causes a decrease in workability but this effect is less pronounced with lean mixes.

(ii) COMPRESSIVE STRENGTH:

An increase in fine aggregate content generally decreases the strength of concrete mix, hence mixes made with grading No.3 possess the lowest compressive strength.

Figures 4(A) to 4(C) show that for a given degree of workability and water/cement ratio the mixes made with grading No.3 have the lowest compressive strength. This is due to its very high sand content. A mix with the highest sand content will normally require additional mixing water to produce a given workability and hence a reduction in strength will be expected. This effect is more pronounced with rich mixes:

6.3.2. THE EFFECT OF WATER/CEMENT RATIO:

(i) WORKABILITY:

As can be seen from Table 14 and Figures 6(A) to 6(C), the compacting factor values increase as the water/cement ratios increase at a given aggregate/cement ratio. The effect of change in water/cement ratio is more pronounced in rich mixes than in lean mixes.

(ii) COMPRESSIVE STRENGTH:

Figures 5(A) to 5(C) show that at a given aggregate/cement ratio an increase in water/cement ratio causes a decrease in compressive strength. The rate of decrease in strength is reduced as the aggregate/cement ratio increases.

In designing high strength concrete, the commonly adopted technique is to use as low a water/cement ratio as possible, that will just be sufficient to enable full compaction to be obtained. As previously remarked, a reduction in water/cement ratio causes a decrease in workability and an increase in strength of concrete. However, at a point, further reduction in water/cement ratio will fail to cause an increase in strength because full compaction may be prevented.

6.3.3. THE EFFECT OF AGGREGATE/CEMENT RATIO.

The term 'aggregate/cement ratio' may be defined as the ratio of the total aggregate to the cement content in a mix.

i.e. Aggregate/Cement Ratio = $\frac{\text{Weight of Aggregate}}{\text{Weight of Cement}}$.

The ratio used is by weight of the two materials.

(i) WORKABILITY:

The effect of aggregate/cement ratio on workability is shown in Figures 6(A) to 6(C) and Nos. 7(A) to 7(C). As can be seen from the two figures, at a given water/cement ratio an increase in aggregate/cement ratio causes a decrease in workability.

(ii) COMPRESSIVE STRENGTH

Figures 5(A) to 5(C) show the effect of aggregate/cement ratio on compressive strength. An increase in aggregate/cement ratio leads to an increase in compressive strength at a given water/cement ratio. The increase is less pronounced with lean mixes. There is a tendency for a reverse effect to occur at very high aggregate/cement ratios. This may be because the cement content would have been so low that there is inadequate binding matrix in the mix.

At a constant workability a reduction in aggregate/cement ratio is accompanied by a decrease in water/cement ratio and consequently an increase in the compressive strength is achieved. This is an important factor in the design of high strength concrete.

6.3.4. THE EFFECT OF AGE AT TEST:

The rate of strength development of concrete made in the tropics is higher than that of the temperate climates, especially at early ages. The ratios of the increase in strength obtained in this investigation are as follows:-

U_3/U_7 ratio ranges from .74 to .80; average is .76

U_3/U_{28} ,, ,, ,, .58 to .62; ,, ,, .60

U_7/U_{28} ,, ,, ,, .76 to .80; ,, ,, .78

where U_3, U_7 and U_{28} are the strengths at ages of 3, 7, and 28 days respectively. Similar ratios for concrete made in the temperate climates are .67, .50 and .67 respectively.

This indicates that concrete mix design data in use in the temperate countries will most likely underestimate the strength of concrete made in the tropics.

6.4. COMMENTS ON LIKELY SOURCES OF VARIATIONS IN THE TEST RESULTS

Whilst every effort was taken to limit variations in the test results, there were still some differences in the results obtained from specimens in the same group. These variations in the test results on concrete, however, are commonly accepted to be inevitable owing to the nature and characteristics of concrete (23). The variations in the results obtained in this investigation may be due to the following reasons:

(i) variations in the properties of materials used; and

(ii) discrepancies in the testing procedure.

(i) Variations in the Properties of Materials:

Variation in the properties of the materials tested is considered to be the main source of error and the material mostly affected is the cement. During the period of test, several different consignments of cement were used. There was a considerable variation in the quality of cement from batch to batch. Some were more finely ground than the others and the rate of hardening of the individual consignment was noticeable. This variation in fineness will no doubt affect the workability and cohesiveness of the mix, and the

fluctuations in the rate of hardening will have effect on the compressive strength, especially at early ages. The variation was of such an extent that the cube strength for each series of aggregate grading in the main tests cannot be compared with the other series. However, further mixes were made in the check mixes series using a single consignment of cement for each aggregate grading. The results of this check mixes were then used to adjust slightly the design curves so that there is better correlation among the results.

There was very little variation, if at all any, in the qualities of the aggregates used, because they were obtained from the same source in very limited consignments. To provide better control of the mix proportions, the coarse aggregate was sieved and used in two single sizes. The gradings of the fine aggregate was also checked in each consignment and in no case was the difference more than about $\pm$ 2% in any of the particles sizes.

(ii) Discrepancies in the Testing Procedures.

The following factors may have caused discrepancies in the testing methods:

(a) climatic variations; and

(b) non-uniformity in making and testing of specimens.

(a) Climatic Variations.

There were noticeable variations in the temperature and the relative humidity in the laboratory during the time of experimenting. The ambient air temperature during the tests ranged from 79°F to 86°F (21°C to 30°C) and the relative humidity from 50% to 80%. The cubes were cured in water at the room temperature and they were therefore subjected to the effect of the large changes in temperature at day and night, which often occurred in the tropics. These fluctuations in the climatic conditions could contribute to the variation in the test results.

(b) Non-Uniformity in Making and Testing of Specimens.

At no occasion was there any doubt about the accuracy of the weighing or batching of the materials nor during any of the measurements. Due care was taken to limit the loss of materials during the mixing of the concrete to the minimum. Discrepancies in these respects will cause variation in the test results.

The cubes were compacted on a vibrating table until no air bubbles appeared on the surface of the specimen. This is a visual observation only and

7. THE PROPOSED METHOD OF MIX DESIGN

A partly new mix design method has been evolved on the basis of the results obtained in this investigation. The method considers the basic features of concrete mix design and follows the same pattern as the existing design procedure of Road Note No.4 which is the most commonly used method in this country. For example:

(i) the method realises the concept of the importance of the water/cement ratio on concrete properties, and considers the aggregate/cement ratio and aggregate gradings to exert noticeable influence on concrete strength.

(ii) the aggregate grading was determined by the specific surface area method, as it reduces the difficulties of grading the available aggregates to approximate the given standard grading curves.

A concrete mix made with Ordinary Portland Cement, natural sand and crushed granite aggregate of $\frac{3}{4}$-in. maximum size, and cured under normal tropical climatic conditions, may be designed using the information and data presented in this investigation, simply by following either one of the the following alternative procedures:

7.1. PROCEDURE OF PROPOSED METHOD.

1. Decide on the average compressive strength for the particular job. (If the specification gives the minimum strength then the average strength may be estimated by any of the methods given in existing mix design methods [8]).
2. Decide on the degree of workability required for the work by giving consideration to the class of work, the usage, conditions and method of placing the concrete. The degrees of workability adopted are as given in existing mix design data [8].
3. Establish the overall grading of the combined aggregate by determining the best combination of the available aggregates to have approximately the same total surface area as one of the gradings used in this investigation. (The method of determining the total surface area of combined aggregate given in Table 5 may be followed as a guide).
4. Determine the water/cement ratio required to produce the given strength at the specified age using the appropriate curves shown in Figures 4(A) to 4(C); giving consideration to the degree of workability anticipated and the grading of the aggregates.

Alternative Design Procedures

Data that permit alternative steps to be followed in the mix design are given in Figures 5(A) to 5(C) and Figures 7(A) to 7(C).

This alternative design method differs from the above procedure only with respect to steps Nos. 4 and 5.

The water/cement ratio required to produce a given strength may be read off from the appropriate curves of Figures 5(A) to 5(C) if the aggregate/cement ratio to be used in the mix has been ascertained or established. This prodedure will be advisable if the strength and the aggregate/cement ratio have been decided and all that is required is the estimation of the water/cement ratio to give this strength. Figures 5(A),5(B) or 5(C) will be used for grading Nos. 1,2,or 3 respectively.

The alternative design curves to be used in place of Figures 6(A) to 6(C) as described in step number 5 above are those given in Figures 7(A) to 7(C). The required aggregate/cement ratio to give the selected workability and grading at a given water/cement ratio may be determined from the appropriate curves of Figures 7(A) to 7(C). Figures 7(A),7(B) or 7(C) will be used for aggregate grading Nos. 1,2 or 3 respectively.

7.2. EXAMPLE OF MIX DESIGN BY THE PROPOSED METHOD.

Assuming that concrete with an average crushing strength of 4000 lb./sq.in. at 7 days is required for a moderately reinforced concrete structure of average sections, and compacted by vibration and exposed to normal tropical climate.

Design the most economical mix using the following locally available materials:

Cement - Ordinary Portland Cement;

Aggregate - A natural (river) sand of Zone 2 grading and $\frac{3}{4}$-in. maximum size crushed granite, having the following gradings:-

Sieve Sizes:	3/4"	3/8"	3/16"	7	14	25	52	100
Sand :	100	100	100	90	80	40	10	2
Aggregate :	100	40	5	0				

Solution:

Step 1 - Average Strength: 4000lb/sq.in. at 7 days;

2 - Degree of Workability: Medium.
(Decided by giving consideration to usage, condition and method of placing. Table 2 of Road Note No.4 was used as a guide).

Step 3 - Aggregate Grading: Grading No. 2.
(Since the given sand is of Zone 2 grading it will be advisable to attempt to combine the aggregates to match grading No.2.)

Hence, desired combined grading from Figure 1 is:

Sieve Sizes : 3/4" 3/8" 3/16" 7 14 25 52 100

% Passing : 100 55 32 29 24 12 3 1;

and the total surface area value from Table 5 is 827.

4. Water/Cement ratio = 0.60; From Figure 4(B)

5. Aggregate/Cement ratio = 6.0; From Figure 6(B)
= 6.1; From Figure 7(B)
= 5.9; From Figure 15.

6. Aggregate Proportioning:

Proportioning the aggregates by Surface Area method, the calculations are as shown:-

Sieve Sizes	S. A. Index	% Retained		S. A. Value	
		Agg.	Sand	Agg.	Sand
$\frac{3}{4}$"	0	-			
$\frac{3}{8}$"	1	60		60	
3/16"	2	35		70	
No.7	4	5	10	20	40
14	8		10		80
25	16		40		640
52	32		30		960
100	64		10		640
Total		100	100	150	2360

Let % Sand = X, then % Agg. = (100 - X)

Total S.A. of grading No.2 = 827.

S.A. of Agg. + S.A. of Sand = S.A. of Grading 2.

$1.5\ (100 - X) + 23.6\ X = 827$

$22.1\ X = 677$

$X = 30\%$ (approx.)

$\therefore$ % Agg. = (100 - 30)= 70%

Hence, Mix Proportions (by weight) =

Cement	: Sand	: Aggregate	x Water/Cement ratio
1	:(30% of 6.0)	: (70% of 6.0)	x 0.60
1	: 1.8	: 4.2	x 0.60

Step 7- Trial mixes will be prepared in the laboratory using the above proportions and if correction is necessary, this will be made.

8 - Full-scale site trial mixes to be made.

7.3. THE PROPOSED METHOD COMPARED WITH OTHER MIX DESIGN METHODS.

Several mix design methods are in general use and a few of these have been briefly reviewed in Section 1 of this report. As previously noted, the proposed mix design method has some similarity to the British method, in particular, the Road Note No. 4's method. It is intended here therefore to make an empirical comparison with the data and procedures of this method.

The proposed method and the Road Note No.4's method follow the same principle of mix design, in that they are based on the type grading curve method and consider the water/cement ratio as the main criterion of strength. What distinguishes them basically are:

(a) the method of determining the aggregate grading -

In the proposed method, the aggregate grading is assessed by both the surface area method and the typical grading curve method, so that if difficulty arises in approximating to a particular grading curve then the other method may be resorted to; whereas in Road Note No.4, the actual grading is only compared with a number of typical curves.

(b) the method of proportioning -

In the writer's method, the aggregate grading and the degree of workability must be known first before the water/cement ratio for a particular strength could be estimated; whereas in Road Note No.4, the water/cement ratio is determined direct without giving consideration to the aggregate grading and the degree of workability anticipated.

Alternative design curves (Figures 5(A) to 5(C)) were also given by the writer from which the water/cement ratio may be read off if the aggregate/cement ratio had been previously decided.

The writer and Road Note No.4 both present similar Tables from which the aggregate/cement ratio for the mix can be determined, but the writer gives several other alternative methods. For example, either Figures 6(A) to 6(C) or Figures 7(A) to 7(C) may be used to estimate the aggregate content of a mix.

The mix proportions to attain the desired degree of workability may also be determined from either Figures 6(A) to 6(C) or Figures 7(A) to 7(C).

Comparison of Results.

It is difficult to make direct comparison of the results obtained in this investigation with those of Road Note No.4, because the properties of the materials used and the detailed test results were not known. Comparison is therefore confined to empirical terms and is based on the results obtained when the given example of mix design using the proposed method was also designed using Road Note No.4's data. The following results are obtained:

water/cement ratio: 0.46, and aggregate/cement ratio: 3.8; as compared with 0.60 and 6.0 respectively obtained by the proposed method. This shows that:

(i) the water/cement ratio value by the writer's method is about 23% higher than that of Road Note No.4.

(ii) The aggregate content is generally appreciably higher than those of Road Note No.4. The average value is about 36%.

The general conclusion that can be derived from the above is that a mix designed in the tropics strictly using the Road Note No.4 will under-estimate the strength and will not lead to economical use of materials.

8. C O N C L U S I O N

8.1. SUMMARY OF INVESTIGATIONS

The purpose of the investigation is to examine the effect of aggregate grading, water/cement ratio and aggregate/cement ratio on the compressive strength and workability of concrete made under tropical climatic conditions. The conclusions of the study are intended to be applied to mix design in the tropics.

The following observations and remarks may be made on the results obtained in this investigation:

(i) The Effect of Aggregate Grading.

(a) The strength of fully compacted concrete is not significantly affected by aggregate grading but grading is of importance as far as it affects workability.

(b) An increase in fine aggregate content or an increase in the total specific surface area value of the combined aggregates causes a slight reduction in the compressive strength, hence mixes made in grading No.3 series possess lower strength than those in grading No.2 or 1.

(c) For a given water/cement ratio and aggregate/ cement ratio, a reduction in total specific surface area, that is, changing from grading No. 3 to 2 or 1, causes an increase in workability.

(d) Mixes made with aggregate coresponding to grading No.1. would possess the highest strength and the highest compacting factor values.

(e) The most suitable grading for low workability or for use with a high cement content mix is grading No.1, which is the coarsest grading; but to obtain a high degree of workability with a lean mix, the finest grading, that is, grading No.3, becomes the most suitable grading. Grading No.1 is prone to segregation when used in lean mixes.

(f) The effect of aggregate grading is more pronounced with rich mixes than in lean mixes and it increases with a demand for low degree of workability.

(ii) The Effect of Water/Cement Ratio.

(a) At a given aggregate/cement ratio, an increase in water/cement ratio decreases the compressive strength but leads to an increase in workability. The rate of decrease in strength is reduced as the aggregate/cement ratio increases.

(b) For a given water/cement ratio, a decrease in the degree of workability will result in an increase in compressive strength provided that full compaction is still obtained.

(c) The effect of water/cement ratio is more distinct in rich mixes than in lean mixes.

(iii) The Effect of Aggregate/Cement Ratio.

(a) At a given water/cement ratio, an increase in aggregate/cement ratio leads to an increase in compressive strength and it causes a decrease in workability; but for a lean mix with an aggregate/cement ratio of about 9.0, a reverse effect tends to result especially at early ages.

(b) At a constant workability, a reduction in aggregate/cement ratio is accompanied by a decrease

in water/cement ratio and consequently an increase in the compressive strength.

(c) Compacting factor values are more sensitive to variation in aggregate/cement ratio of rich mixes and its effect is greater with grading No.3 which is the highest sanded grading.

(d) The effect of aggregate/cement ratio is less pronounced in lean mixes.

(iv) The Effect of Tropical Climate.

(a) The rate of strength gain of concrete made in the tropics is higher than that of a similar concrete made in a temperate climate. It is increased on average by about 15 percent.

(b) The ratio of 3-day to 7-day strength is 0.76; 3-day to 28-day strength is 0.60 and 7-day to 28-day strength is 0.78; for medium strength concrete made in the tropics; as compared with 0.67, 0.50, and 0.67 respectively for similar concrete cast and cured in a temperate climate. The ratio is slightly higher for rich mixes and slightly lower for lean mixes.

(c) The results confirmed the adverse effect of tropical climatic conditions on the workability of concrete.

8.2. SUGGESTIONS FOR FURTHER RESEARCH.

As noted earlier, the scope of the present study is limited in that the design data presented are only applicable to one brand of cement, one type of coarse and fine aggregate, and one size of maximum size aggregate, out of the many types that are in common use locally. The tests on the concrete strength are also limited to the crushing strength and at early ages only. It is therefore suggested that a similar study be carried out to improve on these limitations.

The present data are based on the total water/cement ratio and not on the effective water. The effect of evaporation of the mixing water has also not been considered. For this reason, when these data are applied to aggregates of high water absorption property and when used for field mixes on windy days, the water content may be inadequate for the desired workability and poor strength development may also result. Hence it is recommended that further study be made in these respects.

The main source of variation in the test results obtained in this investigation has been attributed to inconsistency in the quality of the cement used.

Thorough research is advisable on the quality control of the cements at the Cement Works before they are despatched to consumers.

It is suggested that the following two aspects of concrete mix design for the tropics are important and should be investigated:

(i) As the rate of gain of concrete strength is higher in hot climates, there is a tendency to use less cement when the mix design is based on 28-day strength. This results in lower ultimate factor of safety at older ages because the higher temperatures may not yield higher ultimate strength.

(ii) In very rich mixes used for high strength concrete, there is a possibility of reduction in strength of concrete at long ages as hinted by Ridley (7)

It should be emphasized that the Tables and Figures presented in this study are strictly applicable to the materials used in their derivation; but may be taken to be sufficiently general for the design of trial mixes. Hence the need for further trial tests under the prevailing site atmospheric conditions cannot be over-stressed.

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