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(SECOND EDITION)

DESIGN OF CONCRETE MIXES

DEPARTMENT OF SCIENTIFIC AND INDUSTRIAL RESEARCH
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FOREWORD

This second edition of Road Note No. 4 incorporates more information on the method of combining various sizes of aggregates to comply with the desired overall grading and on the method of designing a mix when using an angular coarse aggregate and a natural sand. The examples have been extended to demonstrate these methods. Reference is made to the importance of allowing for the water absorbed by the aggregate in determining the water/cement ratio and to the use of aggregates of large maximum size.

I. INTRODUCTION

This note has been prepared from information obtained during an investigation into the effect of aggregate grading on the strength and workability of concrete which has been described in Road Research Technical Paper No. 5.[1]* The purpose of the present Note is to show how the results obtained in that investigation can be applied to the practice of choosing the mix proportions so as to give concrete of specified properties with the particular aggregates available.

In order to understand the principles governing the choice of proportions of the various constituents in a concrete mix, it is essential to appreciate the relative importance of the factors that influence the quality of the concrete. Concrete must be satisfactory in two states, namely, in the plastic state and the hardened state. The choice of the proportions is governed by both these conditions.

If the condition of the plastic concrete is not satisfactory, it cannot be properly compacted and its structural value is reduced. Thus if there are 5 per cent of air voids due to incomplete compaction the strength will be reduced by 30 per cent, and 10 per cent of air voids will cause a loss of strength of about 60 per cent.[1] Satisfactory compaction can be obtained only if the concrete is sufficiently workable for the methods of placing employed. The property of workability, therefore, becomes of vital importance from the structural point of view, apart from the question of the cost of placing. The figures given later refer to concrete that is thoroughly compacted.

The commonest criterion of the quality of concrete in the hardened state is the crushing strength, since, although a high crushing strength may frequently be of only minor importance in itself, it is usually accompanied by high tensile and flexural strengths together with other desirable features such as good durability and impermeability to water. Moreover, the ease with which crushing strength can be determined adds to its usefulness as a guide to the general quality of the concrete.

* The superscript numbers relate to the list of References on page 7.

II. DESIGN OF MIXES

The problem of the design of a mix for a given purpose may be reduced, in its simplest form, to the question of obtaining a concrete of the required strength and workability at the lowest cost, by a suitable choice of materials and of the proportions in which they are used.

The accompanying tables and curves provide a means of arriving at a reasonably satisfactory and economical choice of proportions. In view of the widely differing characteristics of different aggregates, however, the proportions estimated in this manner should not be considered binding and the engineer should always be prepared to make final adjustments to the mix on the site. Fig. 1 is used to determine the water/cement ratio required to obtain a given strength. The figures given are average values for fully compacted concrete made with Portland cements of average quality and cured at normal temperatures. Further, they refer to the ratios of the free water content of the mix to the weight of cement. The total water content includes (i) absorbed water in the aggregate, (ii) free water in the aggregate, (iii) free water added at the mixer. (This last is equal to the estimated amount of free water required in the mix, less the amount of free water in the aggregates if wet, or plus the amount of water the aggregates will absorb if dry.) Many methods used in determining the moisture content of the aggregate measure only the free water content. If this is the case, the absorption should also be determined and the amount of mixing water adjusted accordingly.

In making a choice of the strength required for any particular purpose, especially if a definite minimum strength is specified, allowance must be made for the normal variation in strength of works test cubes. The amount of this variation depends on several factors, but principally on the accuracy of the batching and control operations and on the uniformity of the raw materials used. Information on the amount of variation to be expected in any particular case has been given in several publications.(2) (3) (4) (5) (6) Where no other information is available the figures given in Table 1 may be taken as a rough guide to the ratio of average to minimum strengths that might occur in typical works. Strictly speaking, however, an absolute minimum strength cannot be given in this way, as there is always a chance of a very low result occurring occasionally. The value for minimum strength given in the table is that which would normally be expected to occur in, say, several hundred results.

Table 2 provides a guide to the degree of workability required for various classes of work, but the selection of the degree will also depend upon the conditions and methods of placing on each individual job.

The required water/cement ratio and degree of workability having been decided, the cement content is determined for the type and grading of the aggregates available. In Figs. 2 and 3 sets of grading curves are shown for ¾-in. and 1½-in. aggregates respectively. These gradings have been chosen so as to give good results with normal aggregates, but they should not be regarded as being in any sense "ideal gradings", as these do not exist.

Tables 3 and 4 show the proportions of cement required to give each of the four degrees of workability with various water/cement ratios, taking into account the grading, size, and type of aggregate. The shapes of aggregate referred to in Tables 3 and 4 are (i) rounded (such as beach and other well-worn gravels), (ii) irregular (such as water-worn river gravels), and (iii) angular (crushed rocks). In the experiments from which the tables were derived, the fine aggregate used was in each case of the same shape as the larger sizes. In Table 3 values for all three types of $\frac{3}{4}$-in. aggregate are included, but in Table 4 it is only possible, so far, to give figures for the $1\frac{1}{2}$-in. irregular aggregate. If other aggregates of this size but of different shape are to be used, a fair estimate of the proportions required can be made by consulting Tables 3 and 4 together; this is illustrated in Example 2 (see p. 5). A comparison of Tables 3(b) and 4 shows that leaner mixes may be used with the larger size of aggregate. To obtain high compressive strength, therefore, the maximum size should be as large as conveniently possible, but it should not normally be greater than one quarter of the smallest dimension in the structure.

The relative importance of the grading of the aggregate in any given case can be assessed from an examination of Tables 3 and 4, and the advantages gained by strict control of grading can be ascertained. The optimum grading for a given set of conditions can be determined. Sieve analyses of the available fine and coarse aggregates should be made, and it may be found possible to combine them in such proportions as to give an overall grading similar to the one required. It may, however, be found more economical to increase the cement content above the minimum required and to use a less satisfactory, but more easily obtainable, grading.

It often happens that the only fine aggregates available have gradings of a type that makes it impossible to combine them with the available coarse aggregates to obtain an overall grading curve similar to the one required. In these cases it will usually be found either that the amount of fine material passing a No. 25 sieve is more than that shown in the curves in Figs. 2 and 3, or that the amount of coarser particles in the sand (between No. 14 and $\frac{3}{16}$-in. sieves) is excessive. In the first case the quantity of sand (i.e., material passing $\frac{3}{16}$-in.) should be reduced by an amount up to 10 per cent of the total aggregate, and in the second case higher sand contents will be required to produce a grading approximating to the one required. A large excess of material between No. 14 and $\frac{3}{16}$-in. sieves in an aggregate produces concrete of a harsh nature which will require increased cement content to give good workability.

When crushed rock is used as the fine aggregate it is often found to contain a rather large proportion of dust passing a No. 100 sieve. Although this material has little effect on the strength of concrete and small quantities may be beneficial from the point of view of workability, large amounts of dust necessitate an increase in the water/cement ratio and should be avoided. The maximum amount of dust normally allowable depends mainly on the nature of the dust, the grading of the aggregate and the degree of workability. In case of doubt it is advisable to make a test of the amounts of water required to produce the same degree of workability with the aggregate in question and with the same or a similar aggregate containing no dust. The differences in strength to be expected in practice could then be estimated by reference to Fig. 1.

If the proportions by weight are to be converted into their equivalents by volume the bulk densities of the materials used must be known. Since these vary considerably no figures can be given, but the time taken to determine them experimentally is quite short. Care must be taken to allow for the bulking of damp sand. It is recommended, however, that for high-class concrete, batching should always be done by weight.

III. METHOD OF COMBINING AGGREGATES

It has been stated above that when two or more aggregates are available it may be possible to combine them to give a grading approximating to the one required. There are a number of methods of estimating the required proportions but the following method is suggested as being one of the simplest. As an example it will be assumed that it is required to combine a fine and a coarse aggregate having the gradings shown in Table 5, in such a way as to correspond with curve No. 1 in Fig. 2 which contains 30 per cent passing a $\frac{3}{16}$-in. sieve.

(1) A piece of squared paper is marked with percentage scales along three sides as shown in Fig. 4.

(2) The grading of the fine aggregate is marked off along the left-hand vertical axis by marking points and numbering them with the sieve size or number such that the ordinate of each point represents the percentage of material passing that sieve.

(3) The grading of the coarse aggregate is marked off along the right-hand axis in a similar manner.

(4) Each point on the left-hand axis is joined by a straight line to the point with the same sieve size or number on the right-hand axis.

(5) A vertical line is drawn through the point where the sloping line representing $\frac{3}{16}$-in. intersects the horizontal line representing the percentage of material passing a $\frac{3}{16}$-in. sieve required in the combined grading (in this case 30 per cent).

(6) The ordinates of the intersections of the combined aggregate line drawn in (5) with the sloping lines drawn in (4) represent the grading of the combined aggregate as shown in the fourth column of Table 5. The percentage of fine aggregate, as delivered, required in the total is read on the top scale, where this is intersected by the combined aggregate line (in this case 25 per cent).

This method takes into account only one point on the grading curve to which the aggregate is required to approximate. Comparing the combined grading with curve No. 1 in Fig. 2, the percentage passing the $\frac{3}{16}$-in. sieve necessarily agrees but in general the other values do not. In the present case the discrepancy is in no case greater than 3 per cent and is unimportant. If however the discrepancies are large, the proportions may be changed by shifting the combined aggregate line to the right or left so that the discrepancies are reduced.

Where three aggregates are to be combined, two should be combined first, and the resulting grading combined with the third. If two coarse aggregates (say $1\frac{1}{2}$-in. single sized aggregate and $\frac{3}{4}$-in. to $\frac{3}{16}$-in. graded aggregate) are to be combined with a sand, the two coarse sizes should first be combined, using the percentage passing a $\frac{3}{4}$-in. sieve as the criterion. If two sands are to be combined, the criterion should be the amount passing a No. 25 sieve.

When an aggregate has been adjusted to conform approximately to one of the gradings in Fig. 2 or Fig. 3 it does not necessarily follow that the grading is ideal for the purpose. Thus a mix may be such that it is readily compacted but is too harsh for a smooth surface to be obtained. In such a case the grading should be finally adjusted on the site until it is found to be satisfactory. Usually these adjustments involve only minor alterations to the ratio of fine to coarse aggregate.

IV. EXAMPLES

Example 1.

It will be supposed that the concrete is required for use on road work, that it is to be compacted by power-operated machines, that ordinary Portland cement is to be used, that the aggregate will be supplied in two sizes, ($\frac{3}{4}$-in. to $\frac{3}{16}$-in. gravel, and river sand) and that the concrete is to have a minimum strength of 4,000 lb./sq.in. at 28 days.

Reference to Table 1 shows that under such conditions the minimum strength may be expected to be about 60 per cent of the average strength. The average strength to be aimed at in the mix design procedure would, therefore, be $4{,}000 \times \frac{100}{60}$ or 6,700 lb./sq.in. at 28 days, which, on reference to Fig. 1, is seen to require a water/cement ratio of 0·41, say 0·40.

It is now necessary to determine the degree of workability required, and Table 2 shows that "very low" workability would be suitable for road work using power-operated vibrators. This will therefore be used.

Reference to Table 3(b) will then give the cement content for each of the four gradings given in Fig. 2. Thus, if the line marked water/cement ratio 0·40 is followed across to the columns headed "very low" workability, it will be seen that the aggregate/cement ratios required for each of the gradings are as follows:—

Grading No. 1……4·8:1
Grading No. 2……4·7:1
Grading No. 3……4·7:1
Grading No. 4……4·0:1

It will be most economical therefore if the grading of the aggregate can be made to approximate roughly to grading No. 1.

Suppose sieve analyses of the sand and gravel give the figures shown in Table 5. It has already been shown that in order to approximate to grading curve No. 1 these particular aggregates should be combined in the proportions of 25 per cent of the sand to 75 per cent of the gravel. The proportions to be used then become 1 part of cement to 4·8 parts of combined aggregate containing 25 per cent of sand, or, as separate batching would be necessary in practice, 1 part of cement to $4{\cdot}8 \times \frac{25}{100} = 1{\cdot}2$ parts of sand and $4{\cdot}8 \times \frac{75}{100} = 3{\cdot}6$ parts of gravel, the water/cement ratio being 0·40. The proportions may be conveniently written in the form 1:1·2:3·6/0·40. The proportions stated are in all cases by weight.

Notes. The following points should be noted:—

(1) Differences in grading from curve No. 1 to curve No. 3 have little effect on the mix proportions, and therefore the grading may be adjusted over a comparatively wide range to give the most suitable mix without appreciably altering the aggregate/cement ratio.

(2) If the more accurate figure of 0·41 had been taken for the water/cement ratio and the required aggregate/cement ratio found by interpolation in Table 3(b) this would have been 5·0:1, thus giving a slightly leaner mix.

(3) If, while still using only two sizes of aggregate, good control were exercised in all other phases of the work, then a ratio of minimum strength to average strength of, say, 70 per cent might be used. The proportions would then become 6·5:1 with a water/cement ratio of 0·47.

Example 2.

It will be supposed that the requirements are the same as before but that good control will be exercised and the aggregate will be used in three sizes, nominally $1\frac{1}{2}$-in. single-sized crushed rock,* $\frac{3}{4}$-in. graded rock* and Class A natural river sand,* the gradings being as shown in Table 6.

The supply of aggregates in three sizes enables the degree of control to be placed in the first category in Table 1, in which

* These terms refer to the definitions given in B.S. 882:1944, Tables 2 and 3.

the minimum strength is estimated as 75 per cent of the average strength, which should therefore be $4{,}000 \times \frac{100}{75} = 5{,}300$ lb./sq.in.

From Fig. 1 this is seen to require a water/cement ratio of 0·50 and as before "very low" workability will be used.

There is no table of aggregate/cement ratios appropriate to $1\frac{1}{2}$-in. crushed rock used with a natural sand, but an estimate can be made by examining Tables 3(b), 3(c) and 4 together. For a water/cement ratio of 0·50, the entries under "very low" workability are found to be:

Grading	$\frac{3}{4}$-in. irregular	$\frac{3}{4}$-in. angular	$1\frac{1}{2}$-in. irregular
No. 1	7·2:1	6·5:1	7·7:1
No. 2	6·8:1	5·8:1	7·7:1
No. 3	6·5:1	5·4:1	7·1:1
No. 4	5·9:1	5·0:1	6·3:1

If the grading can be made to approximate roughly to grading No. 1 the leanest mix may be used. The relative proportions of the $\frac{3}{4}$-in. and $1\frac{1}{2}$-in. aggregates may be expressed as:—

$$\frac{\frac{3}{4}\text{-in. angular aggregate}}{1\frac{1}{2}\text{-in. angular aggregate}} = \frac{\frac{3}{4}\text{-in. irregular aggregate}}{1\frac{1}{2}\text{-in. irregular aggregate}}$$

In the cases above, and for grading No. 1, this can be written:—

$$\frac{6{\cdot}5}{X} = \frac{7{\cdot}2}{7{\cdot}7}$$

Whence X=7·0. Thus 7·0:1 represents the mix proportions using crushed sand and crushed aggregate of $1\frac{1}{2}$-in. maximum size. It is now necessary to consider the effect of using natural sand instead of crushed sand and the required value will clearly lie between 7·0 and 7·7. Generally the fine aggregate has the greater effect on workability and therefore it is better to give rather more weight to the value appropriate to the fine aggregate. A figure of 7·4 will therefore be taken.

To combine the available aggregates, the two larger sizes of aggregate are first combined in the manner already explained, the diagram being shown in Fig. 5a. From curve No. 1 in Fig. 3 it will be seen that of the material larger than $\frac{3}{16}$-in. 26 parts in 76 or 34 per cent, pass the $\frac{3}{4}$-in. sieve. Marking this value on the $\frac{3}{4}$-in. line it is seen that 23 per cent of the $\frac{3}{4}$-in. to $\frac{3}{16}$-in. material is required with 77 per cent of the $1\frac{1}{2}$-in. material. The resulting grading (shown in Table 6, fifth column) must now be combined with the sand. The diagram for the final combination is shown in Fig. 5b, the required amount of material finer than $\frac{3}{16}$-in. being 24 per cent (Fig. 3). It is seen that 22 per cent of the sand is required with 78 per cent of the combined coarse aggregate. The proportions are therefore 1 part of cement to $7{\cdot}4 \times \frac{22}{100} =$ 1·63 parts of sand to $7{\cdot}4 \times \frac{78}{100} \times \frac{23}{100} =$ 1·32 parts of $\frac{3}{4}$-in. to $\frac{3}{16}$-in. gravel and $7{\cdot}4 \times \frac{78}{100} \times \frac{77}{100} = 4{\cdot}45$ parts of the $1\frac{1}{2}$-in. gravel. The mix proportions arrived at in this example are leaner than those in Example 1 because of the greater degree of control and the use of a larger maximum size of aggregate. The use of an angular coarse aggregate requires a somewhat richer mix than would be required if a gravel of the same size and grading was used throughout.

Example 3.

It will be supposed that the mix is required for reinforced concrete placed without vibration. The minimum strength is required to be 2,500 lb./sq.in. at 28 days and while weigh-batching equipment will be used, the job is not large enough to warrant the highest degree of control. The aggregates readily available are a $\frac{3}{4}$-in. to $\frac{3}{16}$-in. crushed granite and a fine river sand. The sand is normally found to be too fine but may be adjusted by the addition of a coarse sand which is less easily obtained and more expensive. The gradings of the aggregates are given in Table 7.

Reference to Table 1 shows that under these conditions the minimum strength may be expected to be about 60 per cent of the mean value and therefore the mean strength to be aimed at should be $2{,}500 \times \frac{100}{60} = 4{,}200$ lb./sq.in. at 28 days. From Fig. 1 the required water/cement ratio is found to be 0·59, say 0·6. Table 2 shows that "medium" workability would be suitable in this case.

There is no table of aggregate/cement ratios for a combination of crushed rock and river sand, but an estimate may be made by examining Tables 3(b) and 3(c) together. For a water/cement ratio of 0·6 the entries under "medium" workability are found to be:—

Grading	Irregular aggregate	Angular aggregate
No. 1	Segregates	Segregates
No. 2	6·0:1	5·2:1
No. 3	6·0:1	4·9:1
No. 4	5·6:1	4·8:1

The best grading to be used will therefore be No. 2 and the required proportions will lie between 6·0:1 and 5·2:1. The average value of 5·6:1 might be used, but as before it is better to give a little extra weight to the effect of the fine aggregate and therefore a value of 5·7:1 will be used.

It is now necessary to combine the aggregates, considering first the two sands. The diagram is shown in Fig. 6a, and it will be seen from Fig. 2, curve 2, that of the material finer than $\frac{3}{16}$-in. 14 parts in 35, or 40 per cent pass a No. 25 sieve. Since the finer sand is cheaper, however, it may be permissible to raise the value to, say, 45 per cent. It is then seen from Fig. 6a that 35 per cent of the coarse sand is required with 65 per cent of the fine. In Fig. 6b the combined sand is added to the coarse aggregate to give 35 per cent passing the $\frac{3}{16}$-in. sieve. This requires 31 per cent of sand to 69 per cent of the coarse aggregate. The proportions are therefore 1 part of cement to $5{\cdot}7 \times \frac{31}{100} \times \frac{65}{100} = 1{\cdot}15$ of the fine sand to $5{\cdot}7 \times \frac{31}{100} \times \frac{35}{100} = 0{\cdot}62$ of the coarse sand and $5{\cdot}7 \times \frac{69}{100} = 3.93$ of the crushed granite, or 1:0·62:1·15:3·93/0·6. This example serves to show how a small amount of a less easily obtainable aggregate may be used to adjust a grading so that it conforms closely to the desired curve.

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TABLE 1. *Estimated Relation between the Minimum and Average Crushing Strengths of Works Cubes for Different Works Conditions*

Conditions	Minimum strength as percentage of average strength
Very good control with weigh-batching, use of graded aggregates, moisture determinations on aggregates, etc. Constant supervision.	75
Fair control with weigh-batching. Use of two sizes of aggregate only. Water content left to mixer-driver's judgment. Occasional supervision.	60
Poor control; inaccurate volume batching of all-in aggregates. No supervision.	40

TABLE 2. *Uses of Concrete of Different Degrees of Workability*

Degree of workability	Slump in inches*	Compacting factor†		Use for which concrete is suitable
		Small apparatus	Large apparatus	
"Very low"	0 to 1	0·78	0·80	Roads vibrated by power-operated machines. At the more workable end of this group, concrete may be compacted in certain cases with hand-operated machines.
"Low"	1 to 2	0·85	0·87	Roads vibrated by hand-operated machines. At the more workable end of this group, concrete may be manually compacted in roads using aggregate of rounded or irregular shape. Mass concrete foundations without vibration or lightly reinforced sections with vibration.
"Medium"	2 to 4	0·92	0·935	At the less workable end of this group, manually compacted flat slabs using crushed aggregates. Normal reinforced concrete manually compacted and heavily reinforced sections with vibration.
"High"	4 to 7	0·95	0·96	For sections with congested reinforcement. Not normally suitable for vibration.

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

† The "compacting factor" figures have been obtained by means of the compacting factor test for workability described in Road Research Technical Paper No. 5.[1]

TABLE 3. *Aggregate-Cement Ratio Required to give Four Degrees of Workability with Different Gradings and Shapes of Aggregate*

— Indicates that the mix was outside the range tested.

× Indicates that the mix would segregate.

(a) Rounded Aggregate (¾ in. down)

Degree of workability	Very Low				Low				Medium				High			
Grading of aggregate (Curve No. on Fig. 2.)	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Water/cement ratio by weight 0·35	4·5	4·5	3·5	3·2	3·8	3·6	3·2	3·1	3·1	3·0	2·8	2·7	2·8	2·8	2·6	2·5
0·40	6·6	6·3	5·3	4·5	5·3	5·1	4·5	4·1	4·2	4·2	3·9	3·7	3·6	3·7	3·5	3·3
0·45	8·0	7·7	6·7	5·8	6·9	6·6	5·9	5·1	5·3	5·3	5·0	4·5	4·6	4·8	4·5	4·1
0·50	—	—	8·0	7·0	8·2	8·0	7·0	6·0	6·3	6·3	5·9	5·4	5·5	5·7	5·3	4·8
0·55	—	—	—	8·1	—	—	8·2	6·9	7·3	7·3	7·4	6·4	6·3	6·5	6·1	5·5
0·60	—	—	—	—	—	—	—	7·7	—	—	8·0	7·2	×	7·2	6·8	6·1
0·65					—	—	—	8·5	—	—	—	7·8	×	7·7	7·4	6·6
0·70					—	—	—	—	—	—	—	—	×	—	7·9	7·2
0·75													×	—	—	7·6
0·80													×	—	—	—
0·85													×	—	—	—
0·90																

These proportions are based on specific gravities of approximately 2·5 for the coarse aggregate and 2·6 for the fine aggregate

(b) Irregular Aggregate (¾ in. down)

Degree of workability	Very Low				Low				Medium				High			
Grading of aggregate (Curve No. on Fig. 2)	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Water/cement ratio by weight 0·35	3·7	3·7	3·5	3·0	3·0	3·0	3·0	2·7	2·6	2·6	2·7	2·4	2·4	2·5	2·5	2·2
0·40	4·8	4·7	4·7	4·0	3·9	3·9	3·8	3·5	3·3	3·4	3·5	3·2	3·1	3·2	3·2	2·9
0·45	6·0	5·8	5·7	5·0	4·8	4·8	4·6	4·3	4·0	4·1	4·2	3·9	×	3·9	3·9	3·5
0·50	7·2	6·8	6·5	5·9	5·5	5·5	5·4	5·0	4·6	4·8	4·8	4·5	×	4·4	4·4	4·1
0·55	8·3	7·8	7·3	6·7	6·2	6·2	6·0	5·7	×	5·4	5·4	5·1	×	4·8	4·9	4·7
0·60	9·4	8·6	8·0	7·4	6·8	6·9	6·7	6·2	×	6·0	6·0	5·6	×	×	5·4	5·2
0·65	—	—	—	8·0	7·4	7·5	7·3	6·8	×	×	6·4	6·1	×	×	5·8	5·6
0·70	—	—	—	—	8·0	8·0	7·7	7·4	×	×	6·8	6·6	×	×	6·2	6·1
0·75					—	—	—	7·9	×	×	7·2	7·0	×	×	6·6	6·5
0·80					—	—	—	—	×	×	7·5	7·4	×	×	×	7·0
0·85									×	×	7·8	7·8	×	×	×	7·4
0·90									×	×	×	8·1	×	×	×	7·7
0·95									×	×	×	—	×	×	×	8·0
1·00													×	×	×	×

These proportions are based on specific gravities of approximately 2·5 for the coarse aggregate and 2·6 for the fine aggregate

Table 3 (*continued*)

(c) Angular Aggregate (¾ in. down)

Degree of workability	Very Low				Low				Medium				High			
Grading of aggregate (Curve No. on Fig. 2)	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Water/cement ratio by weight 0·35	3·2	3·0	2·9	2·7	2·7	2·7	2·5	2·4	2·4	2·4	2·3	2·2	2·2	2·3	2·1	2·1
0·40	4·5	4·2	3·7	3·5	3·5	3·5	3·2	3·0	3·1	3·1	2·9	2·7	2·9	2·9	2·8	2·6
0·45	5·5	5·0	4·6	4·3	4·3	4·2	3·9	3·7	3·7	3·7	3·4	3·3	3·5	3·5	3·2	3·1
0·50	6·5	5·8	5·4	5·0	5·0	4·9	4·5	4·3	4·2	4·2	3·9	3·8	×	3·9	3·8	3·5
0·55	7·2	6·6	6·0	5·6	5·7	5·4	5·0	4·8	4·7	4·7	4·5	4·3	×	×	4·3	4·0
0·60	7·8	7·2	6·6	6·3	6·3	6·0	5·6	5·3	×	5·2	4·9	4·8	×	×	4·7	4·4
0·65	8·3	7·8	7·2	6·9	6·9	6·5	6·1	5·8	×	5·7	5·4	5·2	×	×	5·1	4·9
0·70	8·7	8·3	7·7	7·5	7·4	7·0	6·5	6·3	×	6·2	5·8	5·7	×	×	5·5	5·3
0·75	—	—	8·2	8·0	7·9	7·5	7·0	6·8	×	×	6·2	6·1	×	×	5·8	5·7
0·80	—	—	—	—	—	—	7·4	7·2	×	×	6·6	6·5	×	×	6·1	6·0
0·85					—	—	7·8	7·6	×	×	7·1	6·9	×	×	6·4	6·3
0·90					—	—	—	—	×	×	7·5	7·3	×	×	×	6·7
0·95									×	×	8·0	7·6	×	×	×	7·0
1·00									×	×	—	—	×	×	×	7·3

These proportions are based on specific gravities of approximately 2·7 for both coarse and fine aggregate

Table 4. *Aggregate/Cement Ratio Required to give Four Degrees of Workability with Different Gradings of 1½-in. Irregular Aggregate*

— Indicates that the mix was outside the range tested.

× Indicates that the mix would segregate.

Degree of workability	Very Low				Low				Medium				High			
Grading of aggregate (Curve No. on Fig. 3)	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Water/cement ratio by weight 0·35	4·0	3·9	3·5	3·2	3·4	3·3	3·2	2·9	2·9	2·8	2·6	2·5	2·7	2·5	2·3	2·3
0·40	5·3	5·3	4·7	4·3	4·5	4·5	4·2	3·8	3·8	3·8	3·7	3·4	3·5	3·5	3·3	3·1
0·45	6·5	6·5	5·9	5·3	5·6	5·6	5·3	4·8	4·6	4·7	4·6	4·3	4·1	4·4	4·3	4·0
0·50	7·7	7·7	7·1	6·3	6·7	6·6	6·3	5·7	5·4	5·7	5·5	5·1	4·8	5·2	5·1	4·8
0·55	—	—	8·1	7·3	7·6	7·6	7·2	6·6	6·2	6·5	6·3	5·8	×	5·9	6·0	5·5
0·60			—	—	—	—	—	7·4	7·0	7·3	7·1	6·6	×	×	6·7	6·2
0·65								8·1	7·8	8·1	7·8	7·2	×	×	7·3	6·9
0·70								—	—	—	—	7·9	×	×	—	7·4
0·75												—	×	×	—	8·0
0·80													×	×	—	—

These proportions are based on specific gravities of approximately 2·5 for the coarse aggregate and 2·6 for the fine aggregate

TABLE 5. *Gradings of Aggregates used in Example* 1

Sieve size	Percentage passing			
	Coarse aggregate	Fine aggregate	Combined aggregate (From Fig. 4)	Grading No. 1 (From Fig. 2)
¾ in.	100		100	100
⅜ in.	31		48	45
$\frac{3}{16}$ in.	7	100	30	30
No. 7	0	92	23	23
No. 14		76	19	16
No. 25		48	12	9
No. 52		20	5	2
No. 100		3	1	0

TABLE 6. *Gradings of Aggregates used in Example* 2

Sieve size	Percentage passing					
	1½-in. crushed rock	¾-in. crushed rock	Sand	Combined coarse aggregate (From Fig. 5)	Combined fine and coarse aggregate	Grading No. 1 (From Fig. 3)
1½ in.	100			100	100	100
¾ in.	14	100		34	48	50
⅜ in.	8	34		14	33	36
$\frac{3}{16}$ in.	2	6	100	3	24	24
No. 7	0	0	78	0	17	18
No. 14			59		13	12
No. 25			40		9	7
No. 52			12		3	3
No. 100			1		0	0

TABLE 7. *Gradings of Aggregates used in Example* 3

Sieve size	Percentage passing					
	Crushed granite	Coarse sand	Fine sand	Combined sand (From Fig. 6a)	Combined aggregate (From Fig. 6b)	Grading No. 2 (From Fig. 2)
¾ in.	100				100	100
⅜ in.	32	100		100	53	55
$\frac{3}{16}$ in.	7	95	100	98	35	35
No. 7	0	70	95	86	27	28
No. 14		46	85	72	22	21
No. 25		14	62	45	14	14
No. 52		6	14	11	3	3
No. 100		0	3	2	1	0

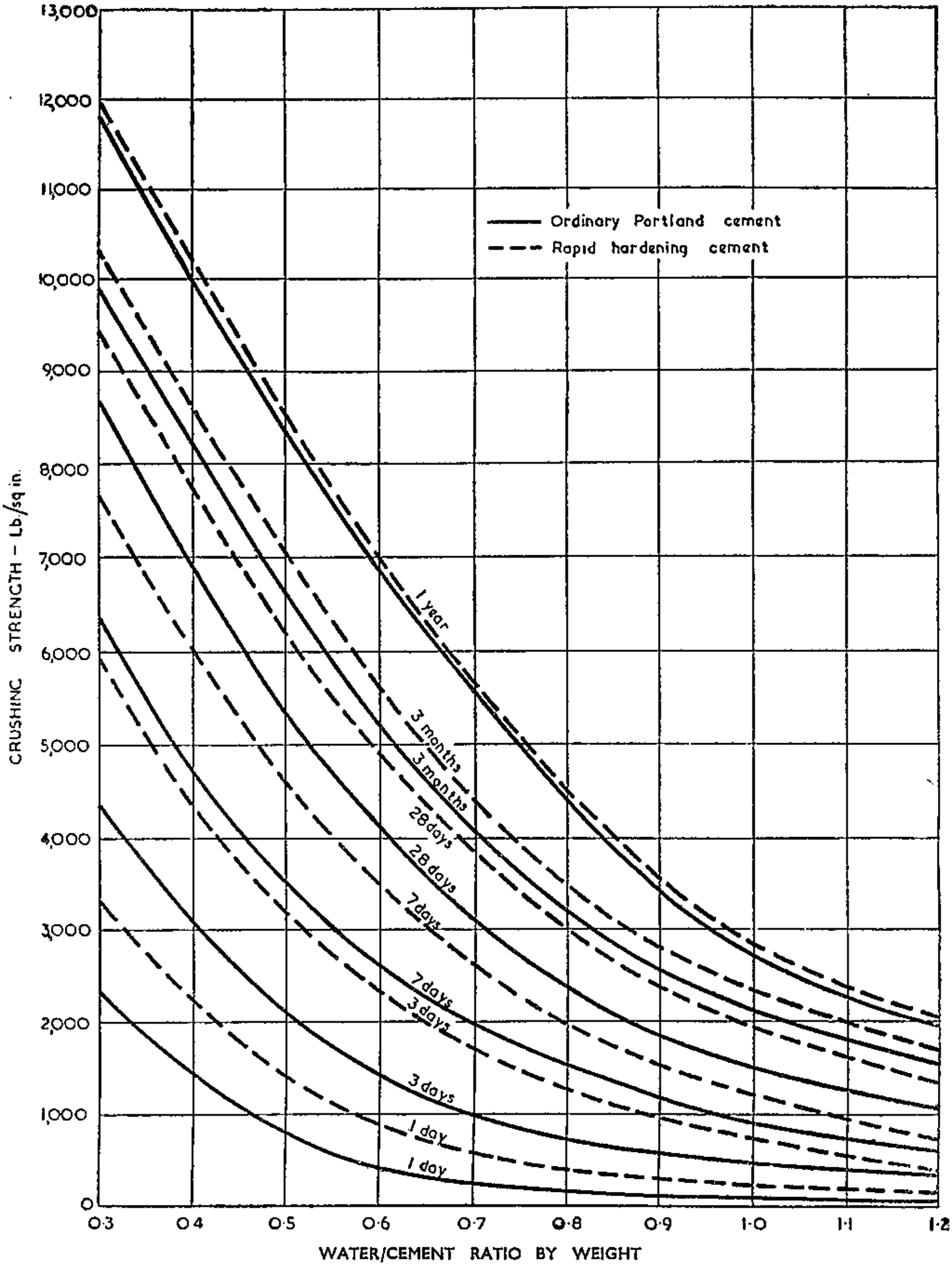

FIG. 1. *Relation between crushing strength and water/cement ratio for 4-in. cubes of fully compacted concrete for mixes of various proportions*

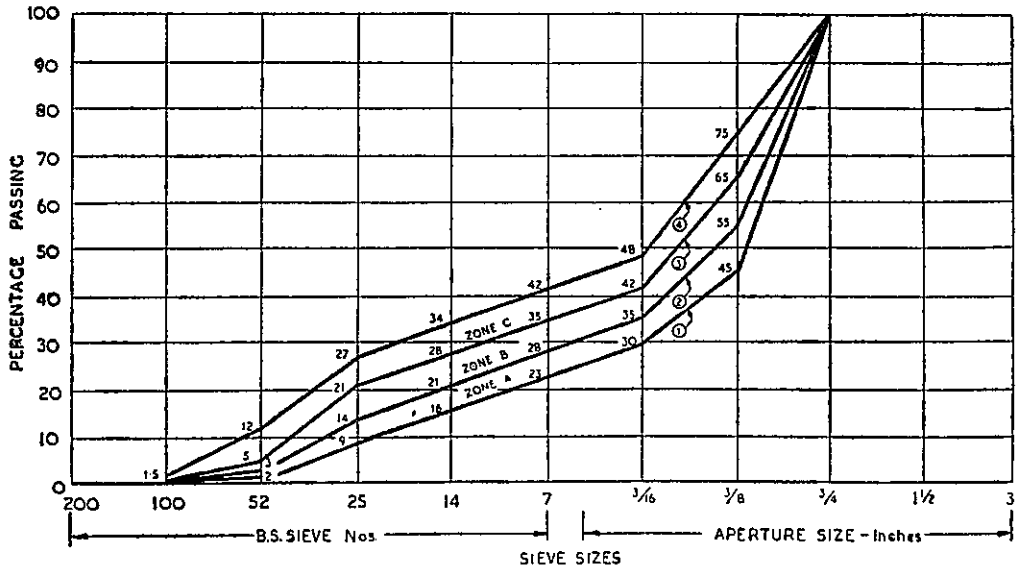

FIG. 2. *Curves of four gradings of ¾-in. aggregate*

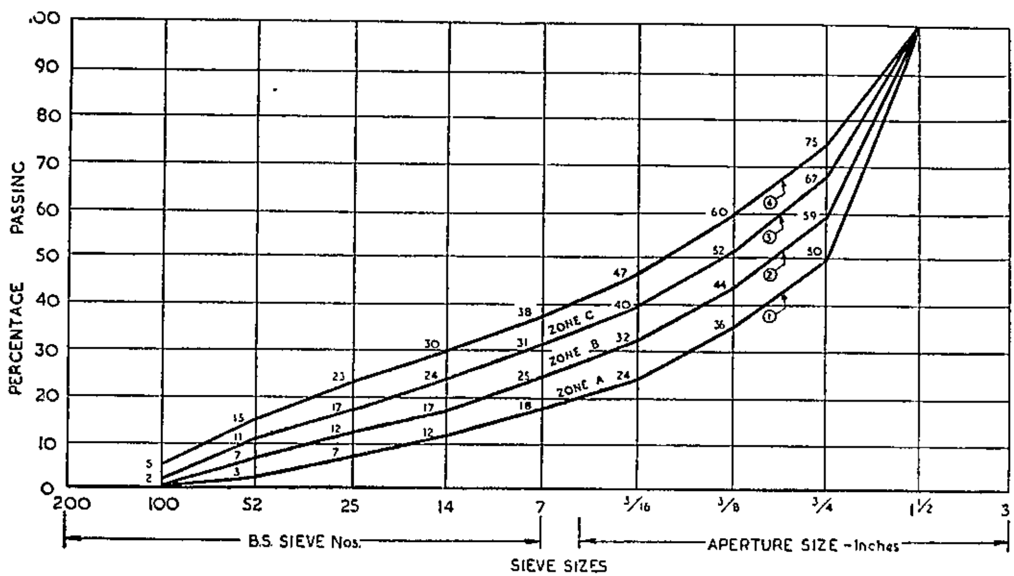

FIG. 3. *Curves of four gradings of 1½-in. aggregate*

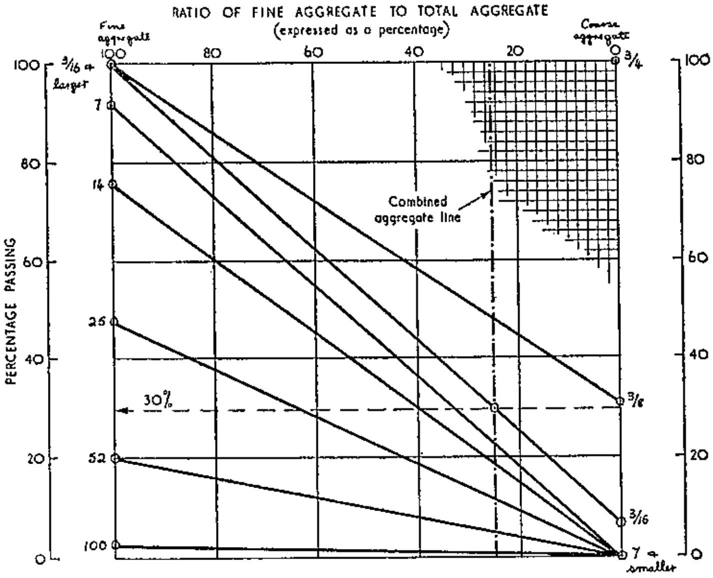

FIG. 4. *Example 1—Proportioning of aggregates*

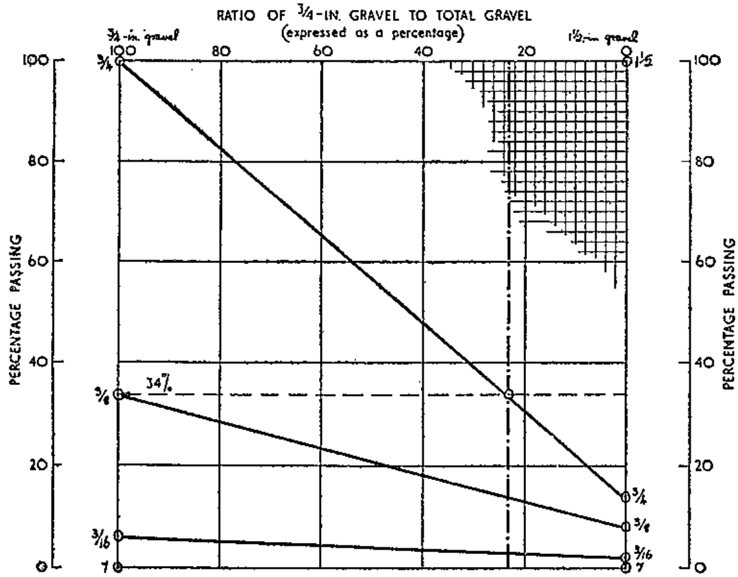

FIG. 5a. *Example 2—Proportioning of aggregates*

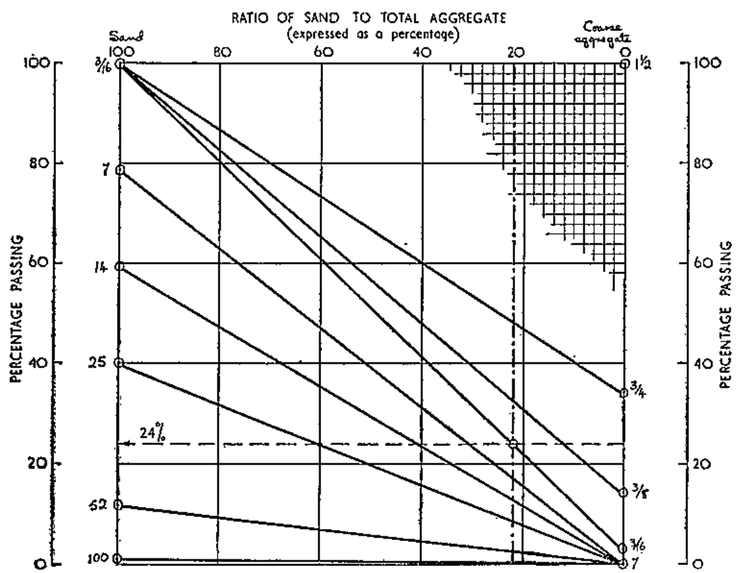

FIG. 5b. *Example 2—Proportioning of aggregates*

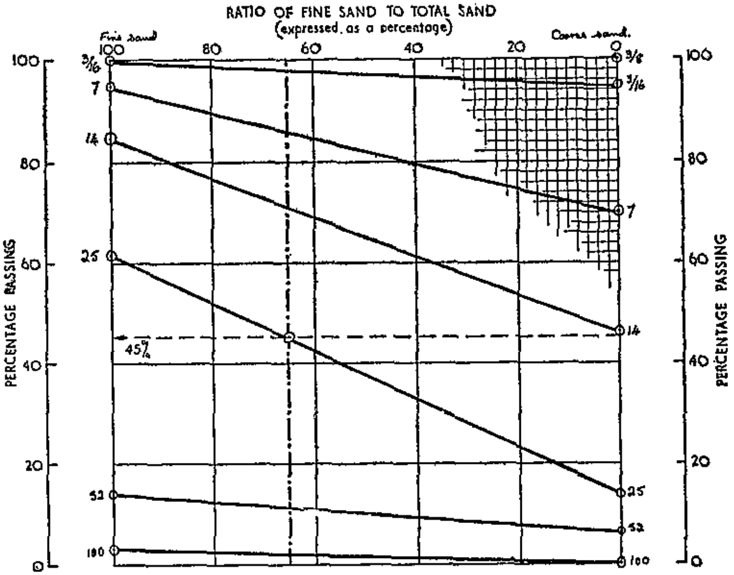

FIG. 6*a*. *Example 3—Proportioning of aggregates*

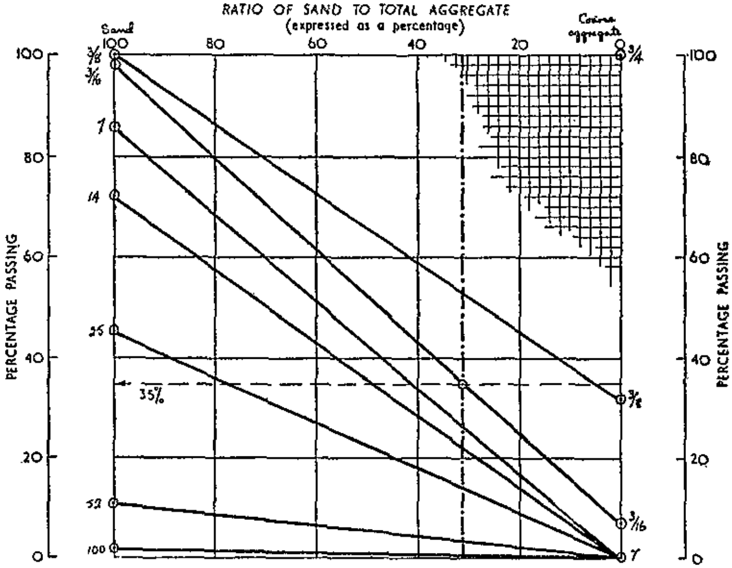

FIG. 6*b*. *Example 3—Proportioning of aggregates*

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