INFLUENCE OF THE GRADING OF AGGREGATES ON CONCRETE MIX PROPORTIONS

Ignatius D. C. Imbert, University of the West Indies, Trinidad

It is well known that aggregate grading directly influences concrete mix proportions and that satisfactory concrete can be produced with aggregates whose gradings do not fall entirely within normal specifications or conform with typical grading curves. In developing countries and particularly on small islands, such aggregates are often the only ones locally available or within economic distance, and the concrete manufacturer has no choice but to select the most suitable mix proportions. The paper discusses the influence of grading on mix proportions and describes the determination of economic proportions using aggregates available on three islands of the eastern Caribbean. On one island, the coarse aggregate consists of coral limestone containing a significant percentage of fines; the fine aggregate is a very fine, uniformly sized sand. On another island, the excessive use of beach sand has necessitated the investigation of concrete-making properties of a local "pumice," a significant fraction of which passes the No. 100 sieve. Results show that, with suitable selection of mix proportions, these aggregates make satisfactory concrete.

•CONCRETE is a mixture that consists principally of water, cement, and aggregates, and one of the most important features of its production is the selection of the proportions of these constituents. The selection must be done in a way that ensures economy and achieves the properties required in the freshly mixed and hardened states.

Among the several important factors that influence the proportions of the constituents of a concrete mixture is the grading of the aggregates. Experience has shown that satisfactory concrete can be made with a wide range of aggregates so long as the mix proportions are suitably selected in accordance with the grading. The selection of these proportions becomes a matter of major importance in developing countries (and particularly on small islands), where it often happens that only one type of aggregate is locally available or within economic distance.

In this paper, the influence of grading on mix proportions is discussed, and a description is given of the determination of economic proportions for a wide range of concrete strengths using aggregates available on three islands of the eastern Caribbean.

GRADING

The term grading refers to the distribution of particle sizes in the aggregates. This distribution is readily obtained by sieve analyses whose results can be easily understood and compared by graphical representation. For this reason, grading charts are used on an extensive scale throughout the world and form the basis of mix design methods recommended by many concrete institutes.

An alternative method of representing grading is the fineness modulus, which is a single factor computed from sieve analyses by adding the total percentages of material retained on each of the standard sieve sizes starting with British Standard or ASTM size No. 100 up to the largest size available. The fineness modulus method is subject to the criticism that it describes the average particle size only, the same modulus representing a large variety of gradings. Nevertheless, it has been shown that, in combination with other factors (1-4), the fineness modulus is very useful in determining mix

proportions, and its use has found favor in the Americas, South Africa, Australia, and other places.

It has been established for some time that grading is a major factor in workability of concrete, and it is appropriate therefore to consider the nature, definition, and measurement of this property of concrete.

WORKABILITY

In its fresh state, concrete must have the property of being handled, consolidated, and finished without segregation or bleeding. This property has a direct influence on its qualities in the hardened state, the most important of which are strength and durability. This influence derives from the well-established relation that exists between the degree of compaction of concrete and its strength (5). The greater the degree of compaction, the smaller the number and size of voids there are, and it is the presence of voids that affects the strength of concrete. Compaction to maximum density can only be achieved if the fresh concrete has adequate workability.

Although there has long been agreement on the conception of what constitutes a workable concrete, there is still little agreement as to its definition. Terms such as workability, plasticity, mobility, and consistence are often used synonymously to describe the same characteristic, whereas they really refer to different attributes of the concrete. Terms such as workable plasticity, which appear in the famous formulation of the Duff Abrams water-cement ratio law (6), make the situation no clearer.

Probably the first serious attempt at a precise and quantitative definition was made in 1947 (5). Workability was defined as "that property of the concrete which determines the amount of useful work necessary to produce full compaction." This property was related to a compacting factor that could be used as a measure of workability. Cusens (7) has shown, however, that the compacting factor is not an accurate measure of the work required to compact dry, harsh mixes with factors of less than 0.80.

Newman (8) has stated that the compacting factor is really a measure of "compactibility" only and has suggested that workability is a composite property of concrete that should be defined in terms of three separate properties: compactibility, mobility, and stability. Hughes (9) has added a fourth property, "finishability," which has been rejected by Uzomaka (10) as not being peculiar to concrete. Uzomaka has further confused the issue, however, by replacing "mobility" with "spreadability" and naming the three properties "consistence."

In view of the confusion surrounding its definition and the complexity of factors involved in its conception, it seems improbable that workability can ever be precisely defined or quantified. The American Concrete Institute, in its excellent recommendations on mix proportioning and consolidation (4, 11), has probably arrived at the best answer to the problem by defining workability as the property of fresh concrete that determines the ease with which it can be placed, consolidated, and finished without harmful segregation. It goes on to say that workability embodies concepts such as flowability, moldability, cohesiveness, and compactibility and relates all three to consistency, which is defined as "the ability of freshly mixed concrete to flow." It further states that, "once the materials and mix proportions are selected, the primary control over workability is through changes in the consistency brought about by changing the water content."

Nearly 60 methods using slump, flow, penetration, drop, mixer, deforming, compacting, and other techniques have been developed over the past 50 years to measure workability. As can be inferred from the foregoing discussion, these have really only succeeded in correlating some aspect of workability or consistency with an easily determinable physical measurement. The vast majority of these methods have found only limited application, and the ones most commonly used today are the slump, consistometer, and compacting methods.

The slump and consistometer methods are tests of consistency, and a direct relation seems to exist between them for ranges of slump from 25 to 100 mm (11, 12). The slump test is relatively insensitive for the drier, stiffer mixes, the consistometer test being similarly so for the wetter, more plastic mixes.

Although there is no obvious connection between slump results and workability, and although the test is so liable to random variations that one cannot readily distinguish among the slumps of mixes of different workabilities, such a relation is of real value as a field control of mixes and is widely and successfully used to indicate the consistency of mixes used in normal construction. In particular, the test will quickly detect a change in water content or grading of a mix of given materials and proportions. The test is of wide application in the Americas and is used as a basis for mix proportioning by the American Concrete Institute (4).

The compacting factor test, developed in Britain, is used there and in many parts of the British Commonwealth mainly as a laboratory tool. Although it is really a test of compactibility only, it provides a reasonably good measure of workability and, in combination with a rough range of slump values (13, 14), is the basis for most mix design methods used in the British Commonwealth.

EFFECT OF GRADING ON WORKABILITY

Apart from hydrating the cement, water lubricates the cement and aggregates in a concrete mix. It is this lubrication that makes the mix workable. The lubricating water evaporates and causes voids when the concrete dries; these should be kept to a minimum. There is therefore an optimum water content that ensures both a workable mix and a minimum number and volume of voids.

Two main characteristics of the aggregates affect the water content of a mix: total surface area and particle interference. Both are functions of grading.

The greater the surface area of the mix constituents, the larger will be the amount of water required to lubricate the surfaces of the particles. A large surface area can be the result of a fine grading or the presence of a large proportion of sharp, angular particles or a combination of both. Obviously, the shape of the particles must influence the grading if a particular surface area is to be maintained, and one cannot escape the conclusion that aggregates having a wide variety of shapes and gradings can have the same total surface area and thus lead to the same water content and workability. It should be noted, however, that the surface area concept breaks down for very fine particles, which appear to have their own lubricating qualities and require less water to wet them. This has led Murdock (15) to devise the surface index method. The apparently inseparable relation between grading and particle shape has also led him to combine them in a formula for the compacting factor.

It is to be especially noted that the packing of the particles must be such as to make it possible for the cement paste to fill the voids in the fine aggregate and for the mortar to fill the voids in the coarse aggregate. This brings us to the second characteristic of the aggregates, particle interference. This occurs when the distance between the larger particles is not sufficient to allow free passage of the smaller ones. The lubricating effect is thus hindered, thereby reducing workability. Moreover, the voids ratio is increased, with consequent effects on strength. The addition of cement paste and/or fine sand forces the larger particles apart, thus increasing the lubricating effect, but this addition creates a need for more water to wet the larger surface area so created and causes a strength reduction if the cement content is not correspondingly increased. Particle interference usually occurs as a result of the fine aggregate containing an excess of larger sizes or the presence of a large proportion of sharp, angular particles in the coarse aggregate, or a combination of both. The situation is probably worst when a finely graded, angular coarse aggregate is combined with a coarsely graded fine aggregate.

It should be clear from the foregoing that the grading of the fine aggregate is far more critical in influencing workability than that of the coarse aggregate because of the larger surface area of the former. If the fine aggregate has an excess of finer particles, with correspondingly large surface area, low workability results. If, on the other hand, it has an excess of coarser particles, the tendency to higher workability caused by the smaller surface area may be offset by the occurrence of particle interference. The ratio of fine to coarse aggregate is therefore of major importance, and it seems that, for any given set of aggregates, there is an optimum combination that

effects a balance between the opposing tendencies of surface area and particle interference (9, 16-20). It should also be pointed out that, for obvious reasons, the effects of surface area and particle interference and hence grading are much less in rich mixes than in lean ones. In the case of rich mixes, it is therefore possible to produce mixes with wide limits of grading and the same workability. Murdock's compacting factor formula (15) takes account of this fact.

As indicated previously, aggregate particles of a given size and shape pack in such a way that free passage between them of smaller ones can only take place if they are sufficiently small. This has led some people to advocate gap grading as the optimum solution to particle interference. It has also been stated (21) that, by using the largest size of coarse aggregate consistent with clearance in structural sections, the reduction of surface area so obtained will lead to higher workability. It has been shown, however, that gap-graded concretes in the more workable ranges are more prone to segregation than continuously graded ones (22), and gap grading is therefore recommended for concretes of low workability that are to be compacted by vibration. Gap-graded concretes also necessitate much closer control than continuously graded ones because they are much more sensitive to changes in water content. With proper control, however, gap-graded concretes have the advantage of requiring less water for a particular workability, thus having a lower water-cement ratio and hence higher strength for a particular cement content.

The use of the largest possible size of coarse aggregate has been mentioned as a way of reducing surface area and thus minimizing the water requirement and cement content. For instance, increasing the maximum aggregate size from 10 to 63 mm can, under certain conditions, reduce the water requirement for a constant consistency by as much as 50 kg/m^3 of concrete and the water-cement ratio by as much as 0.15 (23). Caution must, however, be exercized in increasing the size beyond a certain point because it has been shown that, above a maximum size of 40 mm, the strength gain due to the lower water-cement ratio is offset by the increased heterogeneity of the concrete and the discontinuities created by the presence of very large particles in the mortar matrix (24, 25). For many aggregates, the critical maximum size seems to be as small as 20 mm (26).

WATER REQUIREMENT AND AGGREGATE PROPORTIONS

Tests and experience have shown that the amount of water per unit volume of concrete made with any given set of aggregates and required to have a particular workability is substantially constant regardless of the cement content or water-cement ratio. The different water requirements of various mixes can only be due therefore to the differences in those aggregate properties that influence workability. As indicated previously, the most important of these are grading and particle shape.

If the coarse aggregate is kept the same and if different fine aggregates are used for a series of mixes, it will be found that each mix has a different water requirement that may be called the "water requirement of the fine aggregate." Conversely, we can find the "water requirement of the coarse aggregate." It has been established that there is a much greater variation in the water requirement of the fine aggregate than in that of the coarse aggregate, a condition that can be inferred from the earlier discussion on the surface area of aggregates. As can also be inferred from the foregoing discussion, there is an optimum percentage of fine aggregate (17, 20) that, for any given fine and coarse aggregates used in combination and for a given degree of workability, will require the least amount of water and hence the least amount of cement for a given strength. Therefore, the selection of an overall grading of fine and coarse aggregate is basically the choice of an appropriate percentage of fine aggregate.

MIX PROPORTIONING METHODS

As has been stated, the whole purpose of mix proportioning is to ensure that the properties of freshly mixed and hardened concrete are economically achieved. This reduces primarily to a choice of a suitable combination of materials that are readily available or within economic distance. It is clearly absurd, for instance, to attempt

to adhere to particular aggregate gradings when it is neither possible nor economic to do so. Even when it is possible to do so, one may well find that the grading chosen does not give expected results because the aggregates may differ significantly in shape, texture, and specific gravity from those for which the particular gradings have been developed. The use of particular gradings and other proportions related to them can only serve as "a means of making an intelligent guess at a starting point for the first tests to be made" (27).

During the past 70 years, many methods of mix proportioning have been proposed, but most of these have not been adopted for general use. Among those that are commonly used or are receiving serious attention are those based on arbitrary selection, optimum aggregate content, and specified grading curves. A very useful method combining the concepts of optimum aggregate content and specified grading curves has been developed by Frost (19).

Arbitrary Proportions

The method of arbitrary proportions, in which fixed quantities of fine and coarse aggregate are mixed regardless of size and grading, is highly unsatisfactory and should have been abandoned long ago. It is a matter for great astonishment that specification of concrete in such proportions is still widespread in civil engineering works today.

Optimum Aggregate Content Methods

From the discussion on the existence of an optimum percentage of fine aggregate, it follows that there must also be an optimum percentage of coarse aggregate. This is the basis of the excellent method of proportioning recommended by the American Concrete Institute (4) and, with some slight variations, by the Portland Cement Association (26) and the South African Portland Cement Institute (20). It is also recommended as an alternative in Australia (28).

This method, which is very simple, consists of choosing the consistency of the concrete by selecting an appropriate slump range and the maximum size of coarse aggregate that is economically available and consistent with the dimensions of the structure and the limitations imposed by the heterogeneity of the concrete mentioned earlier. The water requirement is then estimated from published tables or charts or from experience with particular types of aggregates, and the cement content is calculated from the water-cement ratio appropriate to the strength and durability requirements. The optimum volume of coarse aggregate, on a dry-rodded basis and appropriate to the maximum size of aggregate and the fineness modulus of the fine aggregate, is then estimated from published tables. Finally, the content of fine aggregate is calculated by using either the estimated unit weight of concrete or the more accurate method of absolute volumes. Trial batches are made and the proportions suitably adjusted to achieve the required workability.

It is to be noted that the method makes use of the fineness modulus, which is open to certain criticisms. The fineness modulus is only an index of average particle size and hence of the fineness or coarseness of a particular fine aggregate. It gives no indication of particle size distribution, but Fulton (1) has overcome this by using the statistical approach of standard deviation from the fineness modulus as a measure of this distribution. His charts for estimating water requirement use both the fineness modulus and the standard deviation, and they are the basis for the method used for mix proportioning in South Africa. Popovics, in a spirited defense of the fineness modulus (2), proposes the use of the D-m-s method where D is the maximum particle size, m is the fineness modulus, and s is the specific surface. A dispersion index together with the fineness modulus is proposed by Lecompte (3), and Frost (19) has proposed a method combining the concepts of fineness modulus, particle shape, and specified grading curves. One certainty about the fineness modulus is that it makes possible the use of supposedly unorthodox fine aggregate gradings that have been shown to make strong and workable concrete.

In North America, the range of approved fineness moduli is 2.3 to 3.1, but it has been found necessary in other countries to increase the range so that as wide a variety

as possible of fine aggregates can be used. The author has successfully used fine aggregates with moduli as low as 1.9.

The fineness modulus seems to be anathema in Britain where methods based on optimum aggregate content have been developed by Hughes (9, 16, 18, 29) and, in a somewhat different form, by Murdock (15). Both have preferred to use the characteristics of surface area, Hughes developing a grading modulus that he combines with the equivalent mean diameter of the fine aggregate and Murdock combining surface and angularity indexes. Their methods include formulas and charts based on the compacting factor concept of workability as related to the surface area characteristic. Their methods, although excellent contributions to the literature, lack the simplicity and practical nature of the American method based on the fineness modulus of the fine aggregate. It is to be noted that the use of the dry-rodded bulk density of the coarse aggregate in the American method automatically takes account of particle shape.

Specified Grading Curve Methods

Methods using specified grading curves seem to be very popular in the British Commonwealth and some European countries. Perhaps the best known of these is the one given in Road Note No. 4 (13). It is based primarily on combining aggregates in such a way that the grading curve will conform with one of a group of curves that tests at the Road Research Laboratory (5) have shown will give good results.

The method consists of initially choosing an appropriate water-cement ratio and then a related aggregate-cement ratio that will give a particular workability based on the compacting factor. For the particular workability, there are four aggregate-cement ratios corresponding to four specified grading curves. Account is taken to some extent of particle shape by having separate tables of these relations for rounded, irregular, and angular aggregates of 20- and 40-mm maximum size. Similar relations have been published by the Cement and Concrete Association (14) for aggregates having a maximum size of 10 mm.

Although the use of this method results in the production of strong, workable concrete for gradings that are sufficiently close to those specified, it possesses a number of limitations. Some of these are described as follows:

1. The tables and grading curves apply to combinations of similar fine and coarse aggregate commonly available in some parts of Britain. Such aggregates are not necessarily available elsewhere, and it may be impossible to combine them in such a way as to conform with any of the specified grading curves. The combination of crushed stone and natural sand, which occurs in many countries, is not covered at all, and the curves take no account of the fact that many fine aggregates contain a significant fraction of particles passing the No. 100 sieve and that these have a significant influence on the water requirement. Moreover, gap gradings that can make excellent concrete seem to be completely overlooked.

2. It seems that use of the method leads to larger proportions of fine aggregate as this aggregate gets finer. The exact opposite should apply, as has been indicated previously. It also seems that the proportion of fine aggregate to be used is independent of the water-cement ratio, i.e., the wetness of the paste. Experience has shown, however, that the wetter the paste, the larger is the proportion of fine aggregate that can be used in the mix.

3. The water requirement is obtained only indirectly by this method, and it has often been found that significant adjustments to the water content are required to achieve satisfactory workability. The water content is also affected by the percentage of fine aggregate, which is sometimes markedly different from the optimum figure as determined by other methods.

ECONOMIC MIX PROPORTIONS IN THE EASTERN CARIBBEAN

A description is now given of the determination of economic mix proportions of concrete undertaken by the writer, using aggregates available on the three islands of Barbados, St. Lucia, and Trinidad in the eastern Caribbean. These proportions are

based on small-scale laboratory tests and full-scale field trials on concretes with a slump range of 35 to 70 mm and a wide range of water-cement ratios. The slump range chosen represents concrete of medium consistency because this is the consistency required for most of the concrete used on the islands. It should be noted here that, because of the accelerated stiffening of fresh concrete caused by the warm climate and drying winds of the Caribbean (30), the slump range for similar concrete would be about 50 to 90 mm in more temperate climates.

Barbados is an island consisting almost entirely of coral limestone. This rock is the only available source of coarse aggregate on Barbados. The only available fine aggregate except for beach sand, whose use is prohibited, is an inland marine deposit of very fine sand that is largely retained between the No. 25 and No. 52 British Standard sieves. This is clearly shown in Table 1 and Figure 1 for the type A aggregate grading. The sieve sizes shown are based on the British Ready Mixed Concrete Association metric description (31).

Such fine aggregate is not normally considered suitable for strong, workable concrete and, combined with the type A 20-mm coarse aggregate, produces a gap-graded concrete requiring a high degree of control. Fortunately, the type A 10-mm aggregate contains a significant fraction of smaller sizes (Table 1), and a combination of 1:1:1 of the three aggregates produces the grading shown as type A in Table 2 and Figure 2. This grading, based on a judicious assessment of curve No. 4 in Road Note No. 4, has produced a good workable concrete of suitable strength with economic cement content (Table 3 and Fig. 3). The density of the concrete, which is somewhat lower than that of normal-weight concrete and is the result of the specific gravity of the aggregates, appears to have no appreciable effect on strength. The specific gravities are as follows:

Aggregate	Type A	B	C	D
Coarse	2.40	2.28	2.62	2.60
Fine	2.45	2.42	2.56	2.57

It is of particular interest to note that concrete in the higher strength range was successfully used for the post-tensioned ring of the satellite station tower in Barbados and for parking aprons and runways for heavy jet aircraft.

St. Lucia is an island of volcanic origin with long stretches of beautiful beach, which has been the traditional source of fine aggregate for concrete. The boom in construction caused by the rapid development of the tourist industry has led to excessive use of beach sand. This is now threatening the tourist industry itself, and efforts have been made to find alternative sources of fine aggregate. The island has large deposits of pyroclastic material that is called pumice by local geologists. Its specific gravity is, however, much higher than that of normal pumice, and it has satisfactory grading for concrete production (type B aggregate, Table 1 and Fig. 1). The one possible limitation to its use is the rather high fraction passing the No. 100 sieve.

Tests have been made recently on concrete manufactured with this pumice in combination with a sharp, angular, volcanic coarse aggregate of rather low specific gravity (2.28), the only coarse aggregate readily available. A balance had to be struck between the high water requirement necessitated by the grading of the fine aggregate and the gap grading that would be caused by using a relatively small percentage of this aggregate with the available coarse aggregate, the gradation of which is given under type B in Table 1. Gap gradings are not recommended in St. Lucia because the degree of control is suspect. Moreover, the writer's tests have shown a tendency to segregation for such gradings. The combined grading is given as type B in Table 2 and Figure 2 and the mix proportions in Table 3. It is to be noted that the fineness modulus of the St. Lucian fine aggregate is not significantly different from that of the Barbadian one but that the greater standard deviation indicates a need for a somewhat higher water content. The strengths are shown in Figure 3 and are very satisfactory despite the somewhat low density of the concrete resulting from the low specific gravity of the aggregates.

Table 1. Gradings of coarse and fine aggregates.

British Sieve Size	Percent Passing										
	20-mm Aggregate				10-mm Aggregate			Fine Aggregate			
	A	B	C	D	A	B	C	A	B	C	D
20 mm	97	100	98	87	100	100	100	100	100	100	100
10 mm	12	8	26	16	87	99	100	100	100	100	100
5 mm	2	0	2	0	40	15	55	100	100	98	94
No. 7	1	0	1	0	23	0	7	100	99	85	71
No. 14	0	0	0	0	14	0	3	100	92	63	52
No. 25	0	0	0	0	8	2	2	88	68	42	34
No. 52	0	0	0	0	5	0	1	14	35	25	17
No. 100	0	0	0	0	5	0	0	0	15	11	6
Fineness modulus								1.98	1.91	2.76	3.26
Standard deviation								0.51	1.18	2.61	1.65

Figure 1. Grading curves for fine aggregate.

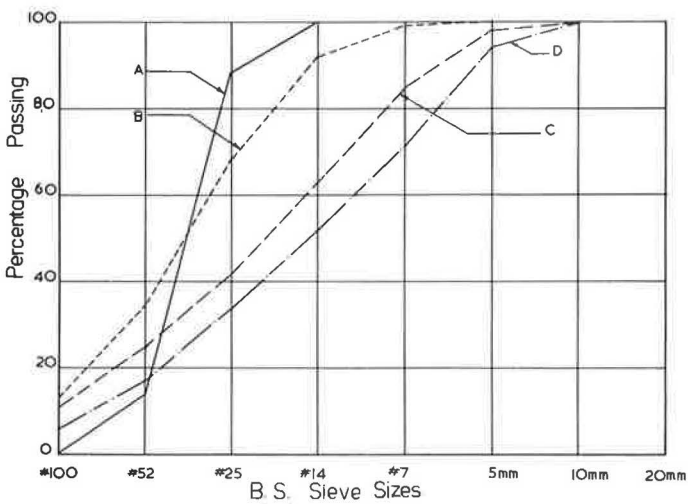

Figure 2. Grading curves for combined aggregate.

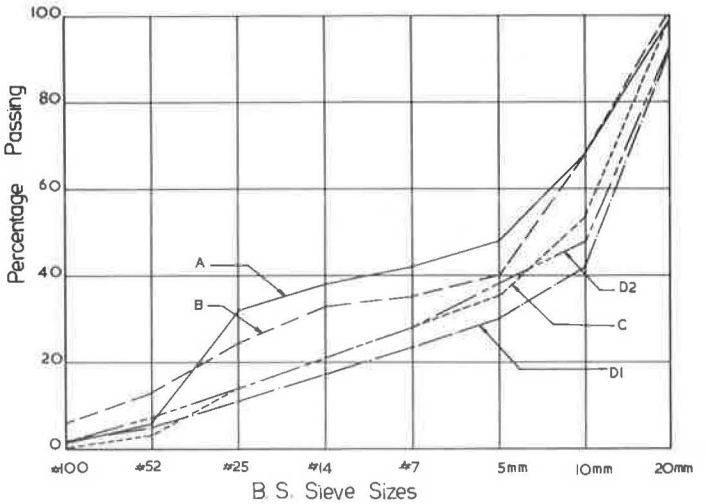

Figure 3. Relation between strength and water-cement ratio.

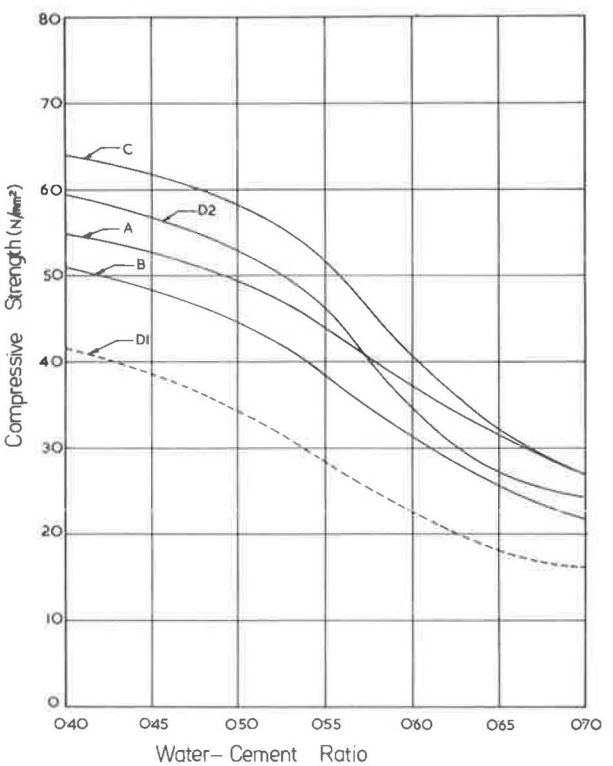

Table 2. Combined aggregate gradings.

British Sieve Size	Percent Passing				
	A (33 percent fine)	B (35 percent fine)	C (32 percent fine)	D1 (32 percent fine)	D2 (40 percent fine)
20 mm	99	100	98	91	92
10 mm	68	68	53	42	48
5 mm	48	40	35	30	38
No. 7	42	35	28	23	28
No. 14	38	33	21	17	21
No. 25	32	24	14	11	14
No. 52	6	13	3	5	7
No. 100	1	6	0	2	2

Table 3. Mix proportions.

Water Cement Ratio	Aggregate-Cement Ratio	Material Weights (kg/m³)						Field Slump (mm)
		Water	Cement	Fine	10-mm Aggregate	20-mm Aggregate	Density (kg/m³)	
Barbados Aggregate								
0.40	3.0	203	507	525	525	525	2,285	50
0.45	3.5	203	454	530	530	530	2,247	50
0.50	4.0	203	407	540	540	540	2,230	60
0.55	4.5	203	372	550	550	550	2,225	60
0.60	5.0	203	337	560	560	560	2,220	50
0.65	5.4	203	312	567	567	567	2,216	60
0.70	5.9	203	293	572	572	572	2,212	60
St. Lucia Aggregate								
0.40	2.9	207	509	517	436	524	2,189	30
0.45	3.3	207	459	530	448	536	2,180	35
0.50	3.6	207	413	540	456	546	2,162	35
0.55	4.2	207	374	549	463	553	2,146	45
0.60	4.6	207	345	554	469	560	2,135	50
0.65	5.1	207	319	560	437	566	2,125	50
0.70	5.5	207	295	566	477	572	2,117	55
Trinidad Melajo Aggregate								
0.40	3.7	189	474	553	88	1,090	2,394	40
0.45	4.3	189	419	568	88	1,121	2,385	50
0.50	4.8	189	377	579	91	1,141	2,377	40
0.55	5.4	189	342	590	91	1,158	2,370	50
0.60	5.9	189	314	596	94	1,172	2,365	50
0.65	6.5	189	289	602	95	1,186	2,361	60
0.70	7.1	189	268	607	95	1,197	2,356	65
Trinidad Guanapo Aggregate								
0.40	4.0	177	443	709	–	1,063	2,392	40
0.45	4.6	177	393	723	–	1,086	2,379	45
0.50	5.1	177	354	735	–	1,100	2,366	40
0.55	5.8	177	321	744	–	1,112	2,354	50
0.60	6.3	177	295	749	–	1,121	2,342	50
0.65	6.9	177	272	751	–	1,130	2,330	50
0.70	7.4	177	254	755	–	1,132	2,318	55

In Trinidad, there are two main sources of aggregate. One is Melajo limestone, designated as type C in the tables and figures, the fine aggregate of which is a naturally occurring sand and the coarse aggregate an irregularly shaped crushed stone. The aggregates can be easily combined in a grading that approximates curve No. 2 in Road Note No. 4 and have specific gravities of the values that produce normal-weight concrete. The fine aggregate falls within the British Zone 2 range (Table 1 and Fig. 1) and thus requires less water than the Barbadian one, despite the percentages being almost exactly the same. The mix proportions are given in Table 3 and the strengths shown in Figure 3 where it can be seen that an economical cement content produces quite high strengths. It is of interest to note that the information shown in the tables and figures was used to design a mix of somewhat different proportions, with a maximum aggregate size of 10 mm and a slump of 100 mm, for the post-tensioned ring of the satellite station tower in Trinidad. The concrete had a strength of 70 N/mm^2.

The other main source of aggregate in Trinidad is Guanapo limestone, a river deposit having a specific gravity almost identical to that of the Melajo. The fine aggregate is significantly coarser than that of the Melajo, indicating a lower water requirement for the same percentage. When the specified-grading-curve method was used, however, and a grading that approximates curve No. 1 of Road Note No. 4 obtained (aggregate type D1, Table 2), it was discovered that the water content was much higher than expected (216 kg/m^3). The strengths were also much lower than expected for the various water-cement ratios (D1 curve, Fig. 3). This was a clear example of the specified-grading-curve method being unsuitable for particular mix designs. Another approach was then used, employing the method of estimating the water requirement of the fine aggregate. Not only were the water requirement and cement content significantly less, but the strengths were considerably higher as can be seen from the D2 curve shown in Figure 3. It should be noted that the fine aggregate content was 40 percent, a figure to be expected from its coarse grading. It is also significant that, with this percentage, the combined grading was similar in many respects to that of the Melajo aggregate.

CONCLUSION

Grading and its effect on workability, water requirement of mixes, and mix proportions have been discussed. Emphasis has been placed on the nature, definition, and measurement of workability, the single most important property of concrete in its fresh state. Mix proportioning methods have been discussed and a description given of the determination of economic mix proportions in the eastern Caribbean. It has been shown that satisfactory concrete can be made with a wide variety of aggregates so long as suitable mix proportions are selected. The writer hopes that this paper will widen some horizons and indicate that there is still considerable research to be done on the grading of aggregates and the properties that it influences.

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