COMPATIBLE GRADATION OF AGGREGATES AND OPTIMUM VOID-FILLING CONCRETE PROPORTIONING FOR FULL CONSOLIDATION

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Through the authors' extensive research and development in the key issues of concrete technology and through their wide practical applications from prior to 1949 to the present time, they have recognized the importance of compatible gradation of aggregates and have evolved an optimum void-filling method of concrete proportioning to ensure full consolidation. The method is based on four mutually dependent principles as follows: Compatibility between the grading of the coarse and fine aggregates is an essential factor in accurately controlling the total void content per unit volume of the combined aggregates; by applying the principle of gradation compatibility, engineering quality concretes can be readily designed from sound aggregates although full information may be lacking on some other characteristics of these materials; the compatible gradation of the aggregates and their optimum void-filling proportioning will lead to the formation of a plastic concrete that may be fully compacted even at large aggregate-cement ratios; and it is this concrete of largest aggregate-cement ratio with consistently minimum specific surface that will ensure the greatest economy and still retain compactible workability.

•FOR all given sound coarse and fine aggregates, concrete technology should start with their grading to allow the voids of the compacted coarse aggregate particles in a given volume of concrete to be filled with compacted fine aggregate particles and, in turn, to allow the combined remaining voids of a system of compacted coarse and fine aggregates to be filled with a cement paste at a stipulated water-cement (w-c) ratio, adjusted for admixtures if used, to meet the strength requirement.

This desideratum can be best achieved through gap grading with "permissible" maximum size of coarse aggregate and "admissible" maximum size of fine aggregate. The fixed ratio of permissible and admissible sizes constitutes the criterion for compatible gradation. The fundamental basis of compatible gradation forms the backbone of gap grading. It permits an optimum void-filled concrete, proportioned with mathematical accuracy, to provide the full consolidation that cannot be otherwise obtained.

Full consolidation of fresh concrete is of prime importance in achieving high-quality concrete in the hardened state. First, it enhances density, impermeability, durability, and resistances to wear, freeze-thaw, scaling, and spalling. Second, it greatly reduces shrinkage and creep. Third, it increases compressive strength, modulus of rupture, and moduli of elasticity and rigidity.

Instead of relying on post-placing vibration alone, the best results of full consolidation should start with compatible gradation and optimum void-filling proportioning. These subjects will constitute the central theme of the present paper, as prerequisites to full consolidation before mixing.

FUNDAMENTAL BASIS OF COMPATIBLE GRADATION

Basic Principle

The basic principle of gap gradation or gap grading is to omit the undesirable intermediate sizes lying between a narrow range of the maximum allowable size of the coarse aggregate and the largest admissible size of the fine aggregate and to delete the extreme fines from the conventional continuous gradings. To explain clearly gap grading requires that the terms introduced herein be explained further.

Maximum Sizes of Coarse and Fine Aggregates

In plain concrete, the maximum allowable size of the coarse aggregate will be limited by the available equipment for efficient handling, mixing, and conveyance and by the available vibrating devices for effective consolidation. Where the concrete sections are reinforced or prestressed, the maximum allowable size of the coarse aggregate will be further limited by (a) its free passage through spacings of the reinforcing or prestressing steel or ducts and (b) the clear cover required.

The largest admissible size of the fine aggregate should be slightly less than the size of the side interstices when the coarse aggregate particles are closely compacted. As will be shown in the following rhombohedral form of packing, the largest size of the fine aggregate is not determined by the largest size of voids among the coarse aggregate particles but limited by the admissibility under vibration through its side interstices, often described as "throat openings."

Rhombohedral Form of Packing

As the depletion of suitable natural aggregates becomes more pronounced and the substitution of kiln-fired spherical pellets of uniform size comes into more general use, especially in lightweight aggregates, the condition of packing coarse aggregate nearly to a rhombohedral form will be reached in actual practice. Not only is this form of packing attainable with uniform-sized spherical artificial aggregates, but also it is well known from long experience that rounded aggregates have always produced more workable concretes, whereas elongated or flat particles do not and hence are usually required to be picked out by the more rigid specifications. Thus, in the idealized geometrical model for crushed stone or gravel, it is reasonable to take spheres to represent the aggregates. In general, the average size of coarse aggregate passing one size of sieve and retained on the next smaller size, elongated and flat pieces being removed, does statistically represent an equivalent spherical size.

When such average spheres are packed together, the most stable and efficient packing is in the rhombohedral form. In other words, if the maximum-sized spheres having a diameter D are hand packed in the most efficient way in a container whose three dimensions are large as compared with the diameter D, a rhombohedral form of packing will result.

If these particles with a diameter D are termed "major spheres," the largest voids among their packing will be able to accommodate smaller spheres of diameter 0.414 D, which may be called "major occupational spheres." The then remaining largest voids would geometrically be able to accommodate still smaller spheres of diameter 0.225 D, which may be termed "minor occupational spheres." The residual voids now remaining can be geometrically filled with further smaller spheres of diameter 0.155 D, which may be called "admittance spheres." This geometrical model can go on down to the extreme fines.

In an ordinary sense, for a coarse aggregate of maximum-sized D, and if D is equal to 1 in., those particles with a diameter larger than 0.225 D would be all termed coarse aggregate, and those equal to or smaller than 0.225 D would be all termed fine aggregate. However, the rhombohedral packing is feasible only in very careful hand packing according to a predetermined geometrical model. In practice, neither the major occupational spheres of 0.414 D nor the minor occupational spheres of 0.225 D can enter the side interstices after the major spheres have been closely packed in the rhombohedral form. Only the admittance spheres can enter such side interstices.

The fact just stated will at once become convincing by performing a visual experiment with a three-dimensional container of plate glass sides whose inside dimensions are large as compared with the diameter D of the maximum-sized spherical particles. After laying them closely in rhombohedral form, one may try to overlay them with any size of aggregate smaller than the maximum size D but greater than 0.155 D; it will be seen that it is impossible for any overlying intermediate sizes to settle through the interstices into the voids even with the aid of slight vibration. By changing the overlay to particles equal to or smaller than 0.155 D, it will be seen that they can pass through the interstices, fill the voids, and become compacted even without the aid of vibratory motion, provided both materials are dry. It can thus be proved visually, in confirmation with the geometrical theory, that

1. Any intermediate size of coarse aggregate smaller than a narrow range of the maximum size but greater than 0.155 D cannot be consolidated to achieve the function for filling the voids of the maximum-sized coarse aggregate; and
2. The largest size of fine aggregate particles, in order to serve their function properly as a filler material, must have a diameter not greater than 0.155 D.

This leads to the undesirability of having intermediate sizes of the coarse aggregate in any combination of the conventional continuous gradings.

Undesirability of the Intermediate Sizes of Coarse Aggregate

A close and thorough examination of the undesirable effects of the intermediate sizes of coarse aggregate will reveal the following:

1. Any efficient grading must achieve strength from efficient packing such that compression loads will be mainly transmitted by direct contact among particles of the coarse aggregate rather than through the generally weaker mortar, though tensile and shearing stresses must be transmitted through the latter. The condition of such efficient packing can only be obtained if the coarse aggregate particles are within a narrow maximum-sized range and general spherical shape in the absence of intermediate sizes. Adjacent to point contacts among coarse particles, the mortar shares relatively less compression load by virtue of its generally lower elastic modulus than that of the coarse aggregate.
2. Although the two sizes consisting of major occupational spheres and minor occupational spheres could be laid by hand in a predetermined sequence in the voids of the major spheres, it is, nevertheless, impossible to produce this result through any available process of mixing, depositing, and vibrating. This is because the major spheres or major aggregate particles have greater momentum and arrange themselves first into a compact form, after which the intermediate-sized coarse aggregate particles have no way to fill up the voids by virtue of their inadmissible sizes through the side interstices of the earlier compacted maximum-sized coarse aggregate particles.
3. In continuous gradings, the situation is even worse because the coarse aggregate will contain all sizes, from the maximum size to the size of admissible fine aggregate.
4. All the intermediate sizes of coarse aggregate lying between its maximum size and the admissible size of fine aggregate, in all compositions of the conventional continuous grading, will upon consolidation by vibration have an adverse effect by interfering with the close compaction of the maximum-sized coarse aggregate particles, wedging them out from contacting each other and thereby requiring more mortar and hence more cement and water for any stipulated w-c ratio. The separation of the larger sized coarse aggregate particles prevents them from transmitting compression by direct contact and compels such transmission through the generally weaker mortar.
5. The increased mortar content required by a continuous grading represents the need for additional cement and water per unit volume of concrete, and hence more shrinkage and creep can be expected in continuous grading because of the wedging action of intermediate sizes. There is also a further adverse effect of increased "specific surface" in significantly augmenting the cement-paste requirement. This leads to the necessary consideration of the physical influence of specific surface of aggregates in the next section.

Specific Surface of Aggregates

Apart from the conventional definition of specific surface as the surface area per unit weight, which is erroneous except in one instance where the particles under consideration, crushed stone or gravel or sand, have the same specific gravity, the correct definition of this term should be changed to "surface area per unit volume" in concrete technology.

What one is really interested in with regard to this term is the necessary cement paste for binding the coarse and fine aggregates together after the water needed for lubricating and saturating the aggregates in a surface-dry condition has been otherwise provided. It is, therefore, the cement paste needed at a stipulated w-c ratio for strength, with a quantity of water just sufficient to hydrate the cement without excess that will cause bleeding. In this context, the less the mortar, the less the cement paste, the less the cement, and the consequent reduction in water will give the advantages of producing higher unit weight, higher strength, higher moduli of elasticity and rigidity, less shrinkage, less creep, and higher creep recovery. For all these advantages, the optimum condition can be achieved only when the specific surface is at a minimum.

The specific surface may be defined as k/L, where k is a constant depending on the particle under study. In practice, the calculation of specific surface, except for particles of regular geometric shape, is laborious, particularly so in the case of the fine aggregates applicable to concretes. The determination of the specific surface of such a material may be made by assessment of an equivalent mean dimension, L, representative of the average particle in each size group considered. Except in the cases of flaky and elongated particles, a single mean dimension will allow a simple equivalent geometric solid to be calculated, conveniently a sphere, from which a reasonably accurate determination of the true specific surface may be made.

Alternatively, an average particle volume may be established by weighing a representative group of grains, counting the number, n, in the group, which should be not less than 100, and then dividing the group weight, W, by n and the appropriate specific gravity, p. Then

$$D = \sqrt[3]{\frac{6W}{\pi np}}$$

where D = average particle diameter. Comparing the specific surface of spheres per cubic inch of material where the diameters are 3 in. and 0.003 in., it will be found that the former provides 2 sq in., whereas the latter possesses 2,000 sq in. (The ASTM and British Standard No. 200 sieves coincide as to a square opening of 0.003-in. size.)

Minimization of Void Surface

Concrete is known to lose strength as its void content increases. The minimization of voids can be effectively achieved by appropriately arranging the grading of the selected coarse and fine aggregates to the extent that the total volume of voids left will accept just sufficient cement paste at the required w-c ratio to give the fresh mixture the desired workability.

In a three-dimensional container having sides that are large as compared with the size of particles, it can be visualized that the number of voids is at least equal to the number of particles packed in the system. If there is no arching effect, the size of the individual voids is directly proportional to that of the particles forming the system. Although mathematically the percentage of voids remains constant for any system of equal-sized ideal aggregate, the surface area will increase greatly with the decrease in size of particles.

Consider two identical assemblies of single-sized spheres arranged in their most compact and stable rhombohedral packing in two identical containers large enough to minimize the side effect. In this form of packing every sphere touches 12 others. Each assembly will leave the same total void volume of 26 percent. If the spheres in one of this pair of assemblies are of twice the diameter as those in the other, the number of spheres as well as the number of voids formed by the smaller spheres will be the cube of two or eight times the number in the other system. As the surface of each sphere is equal to $\pi(\text{diameter})^2$ and the volume of each sphere is equal to one-sixth of $\pi(\text{diameter})^3$, both the total surface and the specific surface of the smaller sphere assembly will be twice that of the larger assembly.

In assessing the probable workability of a concrete mixture by the fineness-modulus approach, it has thus been recognized that the total surface area to be coated with cement paste has more significance than either the number or the size of voids.

Consider next any conventional continuous grading. It should be obvious that the voids formed by the packing together of the particles retained on one sieve cannot be filled by those retained on the next smaller sieve because they cannot enter the side interstices of the immediately larger size. The effect of combining two successive aggregate sizes is to induce particle interference, cause wedging action upon compaction, increase the number of voids, reduce the average size, and increase the specific surface as well as the total surface while achieving little or no reduction in total voids. The ultimate effect of this so-called continuous grading is to increase the demand for mortar and, hence, sand, cement, and water.

Therefore, for identical aggregate-cement (a-c) ratios, gap grading will virtually manifest a richer mortar as the result of reduced specific surface than its continuously graded counterpart for the same maximum size of coarse aggregate.

Compatibility of Coarse and Fine Aggregate Sizes

The advantage of using as much permissible maximum-sized coarse aggregate as possible to the point of filling the concrete spatial configurations with its compacted bulk volume is obvious from the foregoing consideration of specific surface. Mathematically, the single maximum size of coarse aggregate is the best. In practice, a narrow range of maximum size may be preferable. If the maximum permissible size of coarse aggregate is 1¼ in., the best range may be passing the 1¼-in. sieve and retained on a 1-in. sieve, calling this lesser average diameter as D.

The compacted bulk volume of this coarse aggregate can only admit through its side interstices fine-aggregate sizes not greater than 0.155 D. A maximum No. 8 sand can then be used, allowing a mortar film on the opposed surfaces.

If intermediate-sized coarse aggregates ranging from those passing the 1-in. sieve to those retained on the No. 8 sieve were also used, they would have a wedging action, increase the specific surface, require more mortar, cause more shrinkage and creep, and produce a concrete lower in density, weaker in strength, and lower in moduli of elasticity and rigidity. The removal of intermediate sizes virtually lowers the specific surface, reduces the cement requirement, and increases the workability.

Additionally, to get optimum results in saving cement, all very fine sand particles should be deleted. Because the specific surface for a No. 200 sand doubles that of the No. 100 sand, there is no advantage in using sand particles finer than No. 100, and in many cases the cutoff point can be set at No. 50 or even No. 30, except when it becomes necessary to vary the range for adjusting workability.

On this basis, as an example, Table 1 gives one way for providing gap-grading ranges of coarse aggregate and compatible fine aggregate for gap-graded concrete.

Table 1. Examples of gap-grading ranges of coarse and compatible fine aggregate sizes.

Gap-Grading Range of Coarse Aggregate		Gap-Grading Range of Fine Aggregate	
Passing Through Sieve (in.)	Retained on Sieve (D) (in.)	Maximum Size ≯ 0.155 D	Deleting Fines Finer Than (No.)
6	4	½ in.	30
4	3	⅜ in.	50
3	2	¼ in.	50
2	1½	No. 8	100
1½	1	No. 8	100
1	½	No. 16	100
¾	⅜	No. 30	100

The data given in Table 1 further indicate that all available sizes from 6 in. down to No. 100 can be effectively utilized as categorically outlined in the following section.

Full Utilization of All Sizes

The compatible gradation just stated amounts to what is technically termed "optimum gap grading." Despite its successful use in England, Israel, India, and West Germany, there remains in the United States an unfounded argument against gap grading from all those who cannot see how to utilize all the available coarse and fine aggregates except the dust. The following four different versatile applications of gap grading can dispel their argument completely:

1. In highway bridge projects, the larger sizes can be best used in abutments, pier footings, and pier shafts; the upper medium sizes in pier bents and girders; the lower medium sizes in stringers and floor beams; and the smaller sizes in slabs, railings, and light posts. The construction sequence is such that they can never be poured at the same time.
2. In precasting plants, the larger sizes of the coarse aggregate can be used in heavy girders and columns, the medium sizes in lighter beams and columns, and the smaller sizes in floor slabs, roof slabs, and wall panels. As a matter of fact, these precast elements will be prefabricated in groups.
3. In building work cast in situ, the larger sizes of the coarse aggregate can appropriately go to foundation mats and retaining walls, the upper medium sizes to lower tier heavy columns and girders, the lower medium sizes to lighter columns and beams, and the smaller sizes to floors, roofs, partitions, and parapet walls. By necessity, they are to be cast in stages.
4. In mass concrete work, the necessity to pour in sections and lifts offers the special advantage of being able to vary aggregate sizes in different sections, in lifts, and even in the hearting and facings within a lift.

If we know the available quantities of each size range of the aggregates, it is an easy matter to program the concreting work with different gap gradings for different stages or for different sections and lifts.

The uniform strength of all stages or of all sections and lifts may be easily controlled by the appropriate w-c ratio for each gap grading.

Thus, there could be no waste in any size of aggregate in any project or plant of a fair size. The concrete technologists should be able to adapt their aggregates in a versatile way, to best utilize their available sizes, rather than be controlled by the conventional continuous grading that requires excessive quantities of cement but does not produce the best concrete possible.

FURTHER CONSIDERATIONS IN AGGREGATE GRADING

Regardless of the view one takes with regard to the grading of coarse and fine aggregates for any concrete, it is obviously most desirable to grade them such that they (a) require the least effort for aggregate synthesis, (b) need the minimum control to achieve the mean strength at the narrowest deviation from the minimum required strength, (c) minimize the cement and water requirements for a given w-c ratio, and (d) maximize the a-c ratio. The latter two are the key to economy in concrete production.

If the conventional continuous grading of all sizes is used to achieve maximum density, as is commonly believed, disappointment will result because the interference and wedging action of the intermediate sizes work to produce the opposite effect. There can never be a guarantee to attain the goal. It is, therefore, futile to work to a grading curve for aggregate synthesis, which is labor- and time-consuming and hence an expensive chore. This process will become much simpler as the number of coarse aggregate sizes is reduced.

The simplest way, as has been confirmed numerous times, is to use gap grading, consisting of a single-sized coarse aggregate (deleting the intermediate sizes), and a range of fine aggregate whose maximum size is not greater than that admissible into the side interstices of the coarse aggregate when compacted, at the same time deleting the relatively extreme fines. Such coarse and fine aggregates will both minimize the cement and water requirements as the result of much reduced specific surface. Not only has the grading variation been virtually eliminated but so also has any inaccuracy in moisture content correction been minimized.

It is in the fines that the moisture content may vary between 1 and 12 percent, and a check on this must be made if any continuous grading is to be used. Although the sand content of the combined aggregate in continuous grading may be 35 percent or even more, the sand content in gap grading is likely to be between 30 and 28 percent of the combined weight of aggregates, depending on the a-c ratio. Hence, the possible error in moisture content for gap-graded aggregates should be at a minimum.

Thus, with gap-graded aggregates, there is an inherent (a) minimization of variation in grading, (b) minimization of error in moisture correction, (c) minimization of segregation as the result of only one narrow range in size of coarse aggregate, (d) minimization of cement-paste content due to reduced specific surface and hence water and cement requirements, and (e) minimization of heat of hydration, drying, shrinkage, and creep.

The compressive strength of concrete at a constant w-c ratio increases with reduced workability; i.e., an increase in the a-c ratio will, on compaction, yield a higher strength. Experience not only has shown the importance of grading, particle shapes, and other physical and chemical properties of the aggregates but has also indicated that the grading of the coarse aggregate has a major influence on strength, workability, and cement economy. All these have led to the emergence of statistical quality control.

For maintaining any desired constant workability and w-c ratio to meet a target strength, an increase in the a-c ratio toward economy in construction can be accomplished by an increase in the maximum and mean sizes of the coarse fraction of the aggregates so as to reduce the specific surface area. In heavy concrete work, unrestricted by the spacing of reinforcing or prestressing steel or ducts, it is the larger sizes that will save more of the cement requirement; the crushing of these larger sizes into smaller sizes should be avoided, thereby saving production costs.

Further, all sizes below the input size to the crusher, because of their reduced size and tendency to have an angular and flaky nature, will reduce workability and even strength and hence demand a higher cement content. It is not merely that the intermediate sizes cause particle interference, produce wedging action, and hence require more mortar, but, additionally, the $^3/_{16}$-in. or finer crushings of very bad shape, when fed back into the natural sand, will degrade the fine aggregate.

THE VOID-FILLING METHOD OF OPTIMUM PROPORTIONING

The foregoing fundamental basis of gap grading and further considerations of aggregate grading will naturally suggest a rational approach to an optimum proportioning method for all available sound aggregates with a mathematical accuracy and an utmost simplicity that can never be achieved with the conventional continuous gradings.

With isolated construction sites and a demand for large quantities of coarse and fine aggregates to be either locally quarried or obtained from the river run, the use of any continuous grading may suffer because of a lack of the required amount of certain critical sizes to meet a supposedly ideal grading curve. In the case of gap grading, however, all available sizes of sound aggregates may be successfully utilized to give an optimum proportioning.

In essence, for each cubic yard of concrete, we need to fill the space with compacted coarse aggregate within a narrow range of the maximum size, fill the voids therein with compacted admissible sizes of fine aggregate to save cement paste, and then fill the remaining voids with a cement paste at the required w-c ratio. Thus, a cubic yard of absolute volume of constituent materials will, in practice, yield a cubic yard of consolidated gap-graded concrete if allowance is made for any mortar that may stick to the inside of a mixer.

This easy-to-use optimum proportioning method is extremely simple. It is adaptable to any given sound coarse and fine aggregate. The unit weight of clean water and the specific gravity of standard portland cement are known. For any sound coarse and fine aggregate to be used, it is only necessary to determine (a) the weight of a unit compacted bulk volume of saturated surface-dry coarse aggregate, (b) its specific gravity, (c) the weight of a unit compacted bulk volume of saturated surface-dry fine aggregate, and (d) its specific gravity. The rest can be mathematically determined. To be more specific, the method may be stated as follows:

1. To achieve the highest possible a-c ratio, and therefore the highest economy in making concrete, fill each unit volume of concrete with compacted bulk volume of saturated surface-dry coarse aggregate of the maximum permissible size within a narrow range.
2. Determine the bulk weight per unit volume of the compacted coarse aggregate and its specific gravity, compute its absolute solid volume, and get its total void volume.
3. Fill this total void with compacted bulk volume of saturated surface-dry fine aggregate from the maximum admissible size down through a moderate range, deleting all the extreme fines.
4. Determine the bulk weight per unit volume of the compacted fine aggregate and its specific gravity, compute its absolute solid volume, and find the remaining void volume of the combined coarse and fine aggregates.
5. The remainder of the void is to be filled with cement paste at a stipulated w-c ratio corresponding to the required strength, adjusted with the absolute volume of any desired admixture(s) that may be used.
6. Compute the absolute volumes of the cement and water required to fill the remaining voids and check that the water content is sufficient to provide a suitable degree of workability for the expected placing conditions. This may be checked in the following manner: Calculate the weights of the individual solids in unit volume of concrete and multiply each by the relevant percentage of water requirement. Thus cement is multiplied by 28 percent, fine aggregate by 10 percent, and coarse aggregate by 0.5 to 2 percent, depending on the maximum size in accordance with the following data:

Coarse Aggregate (in.)	Water Demand (percent)	Remark
$1\frac{1}{2}$	0.5 to 0.75	The lower value is for rounded and the higher for crushed material
$\frac{3}{4}$	1.0 to 1.5	
$\frac{3}{8}$	1.7 to 2.0	

By summing the weights of water calculated and dividing by that of cement per unit volume, the probable water content and w-c ratio for a reasonable degree of workability will be given, which can be compared with that specified. Although this method of checking the water content of the mix is empirical, it is based on theoretical considerations of specific surface and surface tension and has been checked experimentally by Stewart.

7. The a-c ratio by weight will directly follow from the foregoing results.

The value of gap-graded concrete technology lies in the ease with which the seven simple procedures can be applied to the proportioning of concrete mixtures involving any unknown coarse and fine aggregates, with a degree of mathematical accuracy considerably greater than would be possible if a continuous grading were employed.

ADJUSTMENTS FOR VARIANTS IN CONCRETE CONSTITUENTS

All concrete is affected by seasonal diurnal weather conditions both on site and frequently at the points where the aggregates are won. Probably the greatest cause of variations in the strength, density, and yield of the concrete is the lack of control of the water carried into the mix by the aggregates. Should this water fail to be taken into account, then the true a-c ratio would be reduced, and at the same time the w-c ratio would be increased. This may reduce the true yield because part of the water will be expelled or at least brought to the surface as the concrete is compacted and later more volume will be lost as a result of sedimentation (plastic shrinkage).

It is quite essential that all aggregates are monitored at least once a day to check their gradings and moisture contents and in certain circumstances their temperatures.

As the magnitude of a concrete construction work increases in size, because of the large quantities of constituent materials needed, there may exist nonuniformity in quarry products or river-run gravels, in sand pits, in water quality, and even in the composition, melt, and grinding of cements because all of them may not be supplied from a single source of constant quality. For these reasons, rigid quality control must be exercised on all the ingredients of concrete. To reduce the possible variants to a minimum, appropriate control and adjustments should be made from time to time on the following:

1. Quality, fineness, and performance of cement;
2. Quality, maximum and minimum size, and grading control of coarse aggregate;
3. Quality, maximum and minimum size, and grading control of fine aggregate;
4. Moisture content measurements and adjustments in water content;
5. Quality of mixing water;
6. Batching control of all ingredients by weight; and
7. Appropriate adjustments of weights of cement and water if admixtures are introduced.

These controls and adjustments apply whether the concrete is site-mixed or supplied ready-mixed.

It must be emphasized that, with gap-graded aggregates, not only can the maximum, minimum, and average sizes be easily controlled but also the grading control will, in the absence of intermediate-sized coarse aggregate, become greatly simplified, thereby giving minimum liability to segregation, increased uniformity in the characteristics of the aggregates, and least variation in the quality and strength of the concrete they produce.

FULL CONSOLIDATION OF DRY MIXTURES

There is no problem in consolidating readily flowing fresh concrete of very wet mixtures. But under no circumstances will such a mixture make a durable concrete in the hardened state. Consolidation must by nature associate itself with a process of compacting the rather dry mixtures with very low slumps.

In fact, because of the many types of vibrators available for consolidating fresh concrete, there is not the slightest justification today to use any mixture with a slump higher than 2 in., and it is preferable to keep it within 1 in.

Slump is by no means as good a measure for the workability of dry mixtures (with slumps from 0 to less than 2 in.) as is Vebe time. It is being referred to here only for its wide use.

Nearly all reasonably proportioned mixes in the range of a-c ratios from 2:1 to 10:1 with corresponding w-c ratios from 0.25 to 0.65 can be consolidated by vibration. In the hearting of mass concrete, large-sized coarse aggregates ($4\frac{1}{2}$ in. to 3 in.) can be used. Even an a-c ratio of as high as 14:1 was used and consolidated in a Scottish dam.

Any mix can have its own particular maximum consolidation by driving out all air entrapped during batching, mixing, transporting, and depositing and by compacting fresh concrete around all reinforcements and inserts and into all reentrant corners. Such particular maximum consolidation, however, may not be the obtainable optimum, and it does not guarantee the best quality at the minimum cost.

Full consolidation has to be achieved first through optimum proportioning to remove all the adverse conditions. This requires that the optimum functions of the constituents of concrete be utilized and adhered to when proportioning aggregate sizes, quantities, water and cement contents, and ratios for the desired strengths.

With $\frac{3}{4}$-in. maximum-sized coarse aggregate, a "zero-slump" concrete may have a low compacting factor of around 0.67 to 0.69 and can be consolidated without difficulty by vibro-pressure compaction. A concrete of 0- to 1-in. slump may have a medium compacting factor of around 0.77 to 0.79 and can be consolidated with fairly intense vibration. A concrete of ¼- to 2-in. slump may have a rather high compacting factor of around 0.84 to 0.86 and can be easily consolidated either manually or mechanically. With gap grading, though the fresh concrete may appear harsh and even have the lower compacting factor, it is really more workable, requiring no more vibration time, by virtue of its inherent smaller specific surface, than continuous grading.

The generally drier, but not less compactible, gap-graded concrete exerts much less pressure on the formwork and permits earlier stripping of forms to allow sooner reuse and more timely finishing than does the conventional concrete. These advantages, coupled with the much-improved physical and mechanical properties and the great savings in cement, have made gap-graded concrete a more economical concrete that is more readily consolidated.

CONCLUSIONS

The foregoing concepts have been evolved through the authors' extensive research and development in the key issues of concrete technology and through their wide practical applications from prior to 1949 to the present.

To recapitulate in the simplest terms, they are based on four mutually dependent principles:

1. Compatible gradation of coarse and fine aggregates will ensure the feasibility of an optimum void-filling method for concrete proportioning and make it a unique method of mathematical accuracy;
2. Optimum void-filling concrete proportioning will always constitute the easiest and simplest method for rationally designing concrete mixtures out of sound aggregates, even of otherwise unknown characteristics;
3. Compatible gradation of aggregates and optimum void-filling proportioning will realize full consolidation of plastic concrete of the largest a-c ratio; and
4. It is this concrete of largest a-c ratio, having consistently minimum specific surface, that will ensure the greatest economy yet still retain compactible workability.