Concrete mix proportions for a given need can be optimized using coarseness factor, mortar factor, and aggregate particle distribution.

Concrete Mixture Optimization
by James M. Shilstone, Sr.

Concrete mixture optimization involves the adaptation of available resources to meet varying engineering criteria, construction operations, and economic needs. Economic considerations include materials, delivery, placement, and progress time-related costs. Optimization is often informally taken into consideration before and during construction on a non-quantitative basis by "adding half a bag of cement," "cutting the rock 100 pounds and replacing it with sand," or adding a high-range water-reducer. When mixtures are optimized on a quantitative basis, construction productivity will be improved, durability increased and both materials and construction costs reduced.

Methods for selecting cementitious materials factors, entrained air, and initial aggregate proportions have been described in many reports and will not be discussed here. The purpose of this article is to provide a quantitative method for optimizing aggregate proportions and making adjustments during progress of the work. The discussion is based on use of rounded to cubical aggregates and mixtures with ASTM C 494, type A or D admixtures. Research leading to these findings has spanned 15 years. While only one research study is reported here (below), the findings have been demonstrated many times. From this study, we conclude:

- The accepted practice of establishing constant mixture proportions by weight contributes to problems arising from variability in aggregates and construction needs.
- The method for selecting trial proportions is of minimal importance. Arbitrary means are as efficient as complex procedures. The only meaningful factors are the characteristics of the composite.
- Once a composite is identified as fulfilling a need, that combination of materials and adjustment procedures can be translated into a mathematical or graphical model as a mixture design. This should include procedures for making adjustments based upon statistical data and variations in materials and construction needs. A mixture design may be adaptable worldwide and used indefinitely as long as aggregate characteristics are similar except for gradation and specific gravity.
- Mixture proportions are the concrete producer's solution to the design, using those sound resources that are available at the lowest price.
- Current ASTM and similar aggregate grading limits do not contribute to mixture optimization, as such standards do not address gradations of the blends. Aggregates that do not meet ASTM C 33 gradation requirements, but are otherwise acceptable under a quality standard, can be used to with equal ease to produce high quality concrete if they can be controlled to produce a consistent, well-graded composite.
- Construction needs are becoming increasingly complex and must be considered second only to engineering criteria when selecting mixture design alternatives.

There are three principal factors upon which mixture proportions can be optimized for a given need with a given combination of aggregate characteristics:

Fig. 1 — Well graded mixture.

Fig. 2 — Gap graded mixture.

Keywords: aggregate size; concrete; cen mix; proportioning; mortar (material); optimization; particle size distribution; performance; quality control; standards.
The relationship between the coarseness of the two larger aggregate fractions and the fine fraction.

- Total amount of mortar.
- Aggregate particle distribution.

### Mixture objectives

It is difficult to picture the relationship of particles and their behavior during concrete mixing, delivery and placement. Construction of a laid-up stone wall is, in part, comparable to a concrete mixture. The mason selects the large stones and fills major voids with smaller stones and bonds them together with mortar. The amount of mortar needed is a function of the relationship between the two stone sizes. If the large stones are rounded or square and predominately one size, and there are no smaller sizes, the amount of mortar needed to fill the voids is increased.

There is a major difference between the stone wall and the concrete. The wall is static but the concrete must have the rheological properties necessary to provide mixture stability, mobility, and compactability.

Fig. 1 represents the profile of a concrete composite with a good distribution of large and smaller stone particles and the mortar to coat all surfaces and fill the remaining voids. Fig. 2 represents a condition where there are no intermediate particles. Since the volume filled by the smaller stone particles cannot be occupied by the large particles, that volume must be provided by increasing the mortar. Increased mortar means increased sand, cement, and water. Such increases do not lead to the casting of high concrete quality. However, it is not always possible to place and finish mixtures that are optimized for engineering needs alone. The mixture design must be compatible with the construction process to be used.

The concrete represented by Fig. 1 is a uniformly-graded mixture and Fig. 2 is a gap-graded mixture. While either concrete can be blended to produce almost any given strength, there is a vast difference in rheological properties. Normally, gap-graded or near gap-graded mixtures contain a greater amount of coarse particles than shown here but that has an adverse effect upon pumpability and finishability.

### Coarseness factor chart

The Coarseness Factor Chart was developed during an investigation conducted under contract with the U.S. Army Corps of Engineers, Mediterranean Division, for construction of the Saudi Arabian National Guard Headquarters, Riyadh, Saudi Arabia. The architectural design required construction of white cement cast-in-place concrete, sandblasted to produce a uniform exposed aggregate surface. The investigation objective was to confirm the potential for a contractor to produce the specified finish and compressive strength.

Riyadh aggregates met the requirements of ASTM C 33 except for gradation. Samples of local materials were shipped to Materials Testing Laboratory, Athens, Greece, for study. That laboratory had previously been the regional laboratory for the Mediterranean Division but was privately owned at the time. The co-investigators were the author and Wilhelm Voelker, Mediterranean Division.

The aggregate gradations and technical data, including the blend of the two sizes of wadi gravel, are shown in Table 1. Gravel B was used for another series of mixtures but the proportions were poorly selected. The results are used here only to indicate a range where the aggregate blend was too harsh to produce plantable concrete.

Five different mixture proportions were selected to determine the most suitable for use in casting the final samples. The proportions were based upon the ACI 211 procedure except that the trial mixtures used contained 75, 81, 86, 90, and 93 percent of the coarse aggregate dry rodded unit weight. When expressed on the percent of aggregate basis, the coarse aggregate varied from 63.3 to 76.6 percent of the total aggregate absolute volume.

Since architectural samples were to be consolidated by vibrator and the slump was to be less than 3 in. (75 mm), the cylinders were consolidated with the same equipment. That decision was important to evaluate the response to equipment used in the construction and to...
properly consolidate the high coarse aggregate factor mixtures.

The water estimated for each mixture was based upon the assumption that as fine aggregate was decreased, the water requirement would decrease linearly. The first batch cast was the 75 percent mixture and the water was exactly as anticipated. From that point forward, the design water was either too much or not enough.

Table 2 is a summary of the proportions and the test results with the actual water used. That series of tests were done using locally available grey cement. The second series for architectural samples and strength were cast using 83 percent and 86 percent coarse aggregate factors and white cement. The water demand was higher with the white cement than with the local cement due to differences in fineness of grind.

When the construction contract was awarded, a training program for Corps site personnel, architect/engineers, and contractors was held in Dallas, Texas. Aggregates proposed for use in the project were shipped to Dallas and used to prepare trial mixtures. The tests were repeated with both Saudi and Dallas aggregates and the results were comparable. The optimum mixture was used in construction with outstanding success.

Fig. 3 shows the results of tests graphically. The X-axis is the percent of aggregate passing the No. 8 (2.36 mm) sieve and the Y-axis represents both the compressive strength and the water-cement ratio. From Fig. 3, the maximum strength was produced at the lowest water-cement ratio. The strength curve in Fig. 3 is comparable to Proctor Curves used in soil testing to evaluate maximum density of compacted materials. The objective of materials blending for strength is to fill voids with sound, inert filler to reduce the volume of binder needed to produce a sound product. Portland cement concrete is no different except for adjustments for construction needs. Fuller & Thompson reported a means for testing aggregate blends to provide minimum voids.

Each mixture was placed in a pile, a vibrator inserted, and the response observed. The 75 percent mixture responded sluggishly. The 93 percent mixture responded rapidly but voids were left between some of the coarse aggregate particles after consolidation. The 86 percent mixture responded almost instantaneously and resembled a mixture with a 6 in. (150 mm) slump. It was apparent the particle distribution of the mixture and response to vibrator are related.

Fig. 4 is a grading chart showing the aggregate gradations and the combined gradations of the coarsest, finest, and optimum mixtures.

![Concrete Aggregate Grading Chart](image)

Fig. 4 — Combined aggregate gradations.

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The chart used is divided into three segments identified as $Q$, $I$, and $W$. This was based on comments by other mix researchers about the amount and function of the “intermediate aggregate” particles. Intermediate aggregate is defined as those particles that pass the $\frac{3}{8}$ in. (9.5 mm) sieve but were retained on the No. 8 (2.36 mm) sieve. The letter identifications were based on:

$Q$ — The plus $\frac{3}{8}$ in. (9.5 mm) sieve particles are the high quality, inert filler sizes. Generally, the more the better because they reduce the need for mortar that shrinks and cracks.

$I$ — The minus $\frac{3}{8}$ in. (9.5 mm), plus No. 8 (2.36 mm) sieve particles are the intermediate particles that fill major voids and aid in mix mobility or, if elongated and sharp, interference particles that contribute to mixture harshness.

$W$ — The minus No. 8 (2.36 mm) sieve particles give the mixture workability, functioning as do ball bearings in machinery. Due to other connotations of this term, it is possibly a poor choice but was selected because workability at a given consistency is largely determined by the character and amount of this portion of a mixture.

It was found that the aggregate source was immaterial. What was important was the combined grading curve. Of the three curves shown, only one produced the optimum concrete to meet construction needs and produced the highest strength. Based upon these and later observations, there are three important principles that can be stated:

* For every combination of aggregates mixed with a given amount of cementitious materials and cast at a constant consistency, there is an optimum combination which can be cast at the lowest water-cement ratio and produce the highest strength.

* The optimum mixture has the least particle interference and responds best to a high frequency, high amplitude vibrator.

* The optimum mixture cannot be used for all construction due to variations in placing and finishing needs.

A means to translate the findings into a usable reference was the next step. It is accepted concrete technology that as the coarse aggregate becomes finer, the need for sand to fill voids increases. As the sand becomes finer, the amount should be reduced. These principles address sand generically. As much as 20 percent or as little as 0 percent of the sand can pass the $\frac{3}{8}$ in. (9.5 mm) sieve and be retained on the No. 8 (2.36 mm) sieve. They and the same sizes that occur in the coarse aggregate should be identified as intermediate particles. To properly analyze a mixture, it is necessary to separate the aggregates by sieve size and study the distribution of the various sizes.

It was observed from the studies and literature that a simple theory could be stated: “The amount of fine sand required to produce an optimum mixture is a function of the relationship between the two larger aggregate fractions.” Later the following was added: “The amount of fine sand needed to optimize a mixture is a function of the amount of cementitious materials in the mixture.”

This relationship was shown graphically in Fig. 5 with the plus $\frac{3}{8}$ in. (9.5 mm) sieve as a percent of all plus No. 8 (2.36 mm) sieve particles $Q/(Q + I)$ shown on the X-axis and the percent of the total aggregate, with and without adjustment for cementitious materials factor, shown on the Y-axis. A trend of needs can be defined within this framework.

The particle distribution of any mixture can be calculated and the results plotted on the Coarseness Factor Chart. The chart originally conceived is identical to Fig. 5 except for minor differences in style.

The amount of the fine aggregate in a mixture must be in balance with the needs of the larger, inert particles. If there is too much sand, the mixture is “sticky,” has a high water demand, requires more cementitious materials to produce a given strength, increases pump pressures, and creates finishing and erasing problems. If there is not enough sand, the mixture is “bony” and...
creates a different set of placing and finishing problems.

The results of the Athens tests and analysis of numerous other mixtures was the basis for the trend bar location. Some of the points plotted for representative mixtures are shown on Fig. 5. The results produced by these mixtures ranged from surprisingly good, high strength, workable mixtures to those which were a part of litigation or claims. Data from early high-strength concrete was also included. The results of tests that were not acceptable when the Riyadh 3/8 in. (9.5 mm) aggregate was used as shown and helped define the upper end of the trend bar.

The trend bar is a reference only. If the aggregates are well-graded natural sand and gravel or cubical crushed stone, the optimum mixture combined grading can plot in or near the trend bar. Such mixtures generally must be placed by bottom drop buckets or by paving machines. The water demand for these mixtures will probably be the lowest possible. The mixture will respond very well to a large, high frequency, high amplitude vibrator even at a low slump. It cannot be pumped and can't be readily finished in building slab construction. As the construction configuration and placement techniques vary from the ideal, the amount of fine particles must be increased.

The amount of fine aggregate needed is also influenced by the amount of cementitious materials. As cement content is varied, the sand content should be adjusted. One 94-lb (42.6-kg) US bag of cement is approximately equal to 2.5 percent of the combined aggregate. The adjusted amount of workability particles are identified by the abbreviation W-Adj (Workability-Adjusted). From the Riyadh tests, the base relationship for the minus No. 8 (2.36 mm) particles W is the volume equal to six US bags (564 lb [253.8 kg]) of cement. At that factor W and W-Adj are identical. As cement factors vary from 564 lb (253.8 kg), adjustments are made based upon the absolute volume of cement. If the cement factor is higher than 6 bags, W-Adj will be higher than W and vice versa.

General-use mixtures are frequently plotted 5 to 6 percentage points above the trend bar. For a given combination of materials, it is necessary to determine the optimum relationship for varying needs. When changes in materials gradations occur, adjustments can be calculated and the new aggregate proportions selected to closely approximate the original mixture.

**Mortar factor**

The Mortar Factor is an extension of the Coarseness Factor Chart. The mortar consists of fine sand (minus No. 8 [2.36 mm] sieve) and the paste. With reasonably sound aggregates properly distributed, it is the fraction of the mixture that has a major affect upon the engineer's interest in strength, drying shrinkage, durability, and creep. It is also the segment that provides the contractor's need for workability, pumpability, placeability, and finishability. Thus, it is the amount of mortar that is at the center of conflict of interests. Neither should be dominant. A mixture that is optimized for strength and shrinkage but can't be properly placed and compacted will perform poorly regardless of the water-cement ratio shown on reports.

Most problems are caused by sand gradation variations that increase or decrease the amount of minus No. 8 (2.36 mm) sieve particles. Such variations affect the water needed to produce a given slump and cement to maintain strength. The cement is seldom changed. The need for mix adjustments was confirmed and reported by Bloem.3

It might seem that this is the most reliable way to evaluate mixture proportions, but there are pitfalls. Calculated mortar content is heavily influenced by water and entrained air. An entrained air tolerance of ±1 percent of the volume is the equivalent of allowing the volume of water to vary slightly more than 33 lb/yd³ (20 kg/m³). Such a variation can affect mortar content by 0.02 percent and contribute to problems. In addition, as entrained air varies, water demand varies so the effect of the combined tolerances can be significant and cause construction problems.

The mortar factor can be used to judge the adequacy of the water provided in initial mixture proportions. ACI 211 provides guidance for selection of water for each aggregate size. This is fairly accurate when adjustments are made for water-reducing admixtures. Generally when W-Adj is high but the mortar is relatively low, there is not enough water provided in the proportions.

The mortar factor needed for various construction types varies. A mat foundation with the concrete placed before the mat requires less mortar than the same strength concrete cast in a thin slab to be trowel finished. Unless aggregate proportions are adjusted to compensate for differing needs, changes in slump to increase mortar through the addition of water is the only option open to the contractor.

Construction requirements that affect mortar needs should be considered when optimizing a mixture. There are no fixed mortar factors, as they are influenced by particle shape, texture, and distribution. Approximate needs for ten construction classifications are shown below.

- **Class 1:** Placed by steep sided bottom-drop bucket, conveyor, or paving machine. Approximate mortar required = 48 to 50 percent.
- **Class 2:** Placed by bottom-drop bucket or chute in open vertical construction. Approximate mortar required = 50 to 52 percent.
- **Class 3:** Placed by chute, buggy, or conveyor in an 8 in. (200 mm) or deeper slab. Approximate mortar required = 51 to 53 percent.
- **Class 4:** Placed by 5 in. (125 mm) or larger pump for use in vertical construction, thick flat slabs and larger walls, beams, and similar elements. Approximate mortar required = 52 to 54 percent.
- **Class 5:** Placed by 5 in. (125 mm) pump for pan joint slabs, thin or small castings, and high reinforcing
Optimization

continued

steel density. Approximate mortar required = 53 to 55 percent.
Class 6: Placed with a 4 in. (100 mm) pump. Approximate mortar required = 55 to 57 percent.
Class 7: Long cast-in-place piling shells. Approximate mortar required = 56 to 58 percent.
Class 8: Placed by pump smaller than 4 in. (100 mm) Approximate mortar required = 58 to 60 percent.
Class 9: Less than 3 in. (75 mm) thick toppings. Approximate mortar required = 60 to 62 percent.
Class 10: Flowing fill. Approximate mortar required = 63 to 66 percent.

To maintain the water-cement ratio constant, the total cementitious materials factors will vary according to the mortar content. Thus, concrete with a higher mortar content should cost more than that placed under restricted conditions. Decisions to use concrete with low mortar and limited mobility should not be made arbitrarily. In today's construction economy, placement cost is important. A requirement for a low mortar concrete can effect not only direct placement costs but also time of completion and added project overhead.

Aggregate particle distribution

Practically any sound aggregate can be combined to produce a given strength concrete. However, when particles are poorly distributed the mixture can cause both construction and performance problems. In asphalt, poorly graded aggregates can increase the need for filler and asphalt while too many fines can contribute to excessive rutting and flow.

For the same reasons that particle distribution is important in geotechnical work and asphaltic concrete, the aggregate fraction of portland cement concrete must be adjusted to properly fill voids to provide the mobility needed for placement and finishing. Much has been learned about the effects of particle distribution from computer software that analyzes the particle distribution of every mixture for which gradations are provided. Both good and problem mixtures follow consistent profiles.

A deficiency of particles passing the 3/4 in. (9.5 mm) but retained on the No. 8 (2.36 mm) sieve necessitates use of more mortar. Generally sand and water are added, without the addition of cement needed to maintain a constant water-cement ratio, to provide needed mobility for construction.

The typical single size stone and single sand mixes with gradations meeting ASTM C-33 size number 57 (1 in. to No. 4 [25 to 4.75 mm]) standards and concrete sand can cause both placing and finishing problems. Fig. 6 is a computer-generated particle distribution chart for a mixture using aggregates complying with the gradation acceptable by ASTM C 33 size number 57 stone and concrete sand. Such a mixture, if used at a reasonable mortar content, will manifest finishing problems. If the sand is increased to satisfy finishing needs, the strength will decrease because there will be a higher water demand. The overmortared mixture will cause the pumper problems because his line friction will increase.

Fig. 7 describes an ideal solution produced by the addition of a pea gravel that is finer than that recommended by ASTM C 33 for size number 8 (¾ in. to No. 8 [9.5 to 2.36 mm]). This ideal will seldom be possible. Most local aggregates can be blended in such a way as to produce a uniform particle distribution when greater attention is paid to the composite than to individual stockpiles.

Fig. 8 reflects the particle distribution produced using the 1923 ver-
sion of ASTM C 33 and recommendations of the first issue of the Portland Cement Association's Design and Control of Concrete Mixtures. The effectiveness of this distribution can be confirmed by examining concrete that has been in service over 50 years. When the surface is abraded, there will be a high incidence of intermediate particles exposed. This is in contrast to modern mixtures that have a great deal of 1/4 in. (12.5 mm) particles and little else between that size and the mortar.

Most industrial nations and some sections of the U.S.A. use at least three aggregate sizes (2 coarse and 1 fine) to assure more consistent particle distribution. The third aggregate is predominately intermediate size (1/2 in. to No. 8 [9.5 to 2.36 mm]) to provide a bridge between the large particles and the mortar, fill major voids, and increases concrete density. When size number 467 (1 1/4 in. to No. 4 [37.5 to 4.75 mm]) aggregate is specified, three coarse aggregate sizes should be used.

Particle shape has a major effect upon the influence of No. 4 and 8 (4.75 and 2.36 mm) particles. Rounded pebbles or cubically crushed stone are desirable. They improve mixture workability, pumpability and finishability and produce consistent, high strengths with low shrinkage. When these sizes are sharp and flat, they should be limited because they cause mix mobility problems.

Similar information about particle distribution can be observed by plotting the combined aggregate gradation. However, this plot is not as definite as the percent retained on each sieve. When this guide is used, the trend line should be as nearly straight as possible. A good reference is the 0.45 power chart used for asphaltic concrete. For portland cement concrete, the gradations fall off the 0.45 power chart straight line for the coarsest and finest fractions.

Summary
Methods for selecting mixture proportions have been discussed for many years but there has been no consensus of opinion about what constitutes a “good” mixture. That process addresses in-put and does not consider out-put. By use of the three factors discussed here, it is possible to stop the process of submitting a new mix design for every project. All the producer need do is prequalify his mixtures, identify those to be used, and provide statistical performance data.

The aggregates available in most communities are fairly standard and used for many years. The only differences are in gradations and specific gravities. The industry can cope with these variables when attention is given to the mixture rather than to stockpiles. Through use of the methods described herein it will be possible to identify and use exactly the mixture needed for any project, and do it consistently.

This should not be interpreted as a suggestion that everything done today is done incorrectly. However, the current practices are wasteful and contribute to many industry problems such as unnecessarily high costs, poor construction productivity, and reduced durability in the infrastructure. It is an attempt to direct attention to performance practices and concrete out-put rather than in-put. The entire construction industry is moving to performance specifications and concrete should follow.

Each dawn is not a new day in the life of concrete. The day has been continuing for over 50 years and we should know where we want to go to achieve any result. Not every mixture must be adjusted — there is a great deal of flexibility in portland cement concrete. Were this not true, the quality work in place around the world would not have been possible. Needs, materials and construction are changing the accuracy needed for concrete production to improve construction productivity and in-place quality.

References
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Selected for reader interest by the editors.

ACI fellow James M. Shilstone, Sr. is president of Shilstone & Associates, Inc., and Shilstone Software Co., Dallas Texas. A graduate of the United States Military Academy, West Point, N.Y., he has been a member of the Institute for more than 20 years and has served on numerous ACI and ASTM technical committees. He was awarded the Wason Medal in 1978 and the Construction Practices Award in 1987.
The asphalt industry's 0.45 power chart is reference in the preceding article. Patrick Creegan discussed the value of that chart in "Properly Coping with the Low Water-Cement Ratios Required by ACI 350R-83" published in CONCRETE INTERNATIONAL. April 1990. ACI 350 covers sanitary structures.

The chart was developed by Nijboer as a means to describe the ideal combined aggregate gradation for asphalt. This could shown graphically as the log of the sieve opening in microns on the "X" axis and the log of the percent passing on the "Y" axis. The United States Bureau of Public Roads (BPR) verified the work but used a non-log relationship for the percent passing. Since the BPR publication, the asphalt industry has widely used the chart as their standard for selecting combined aggregate gradations. They do not control by control of stockpile as is done for concrete because two or more good materials can be combined but produce a problem combination.

Creegan states, "A straight line on this chart from the origin to the point of 100 percent passing the maximum size aggregate, represents the most dense gradation of an aggregate having that maximum grain size." Such an optimization reduces the need for water to allow the production of concrete with a water-cement ratio less than the specified 0.45. A copy of Creegan's illustration is shown below with optimum combined gradation lines plotted for 1/2", 3/4", 1", and 1-1/2" aggregates.

Asphalt makes use of fine mineral filler while concrete uses cementitious materials. We don't feel inclusion of the cementitious material in the chart will be beneficial unless the objective is the highest strength with the lowest cement factor. In working with seeMAT-A to blend aggregates, one occasion we found the ideal cement factor was 410 lbs. per cubic yard. As a result of not using the finest particles, a concrete gradation falls off the 0.45 power line at about the No. 16 sieve.

The 0.45 power chart and our concepts of mix and aggregate optimization are very similar. When the combined gradation, expressed as percent passing, for Figure 6 is plotted on the 0.45 power chart, there is no correlation. However, the gradation from Figure 7 is very close.

We have found from mix analyses using the seeMIX software program that the cementitious materials factors affects the 0.45 power chart viability and can contribute to using to much sand. The Courseness Factor Chart (Figure 5) is needed to make the correction. The seeMIX program includes the analytical methods and technology discussed the preceding article. Call (800) 782-8649 for more information on the software.

IN SUMMARY: When aggregates and cementitious materials are optimized, concrete quality will be improved, costs reduced by minimizing wasteful use of materials, and long-term durability will be extended.
Concrete is frequently looked upon generically as a nondescript mass. In fact, it is a specific, demanding engineering material. Yet we know little about mixture optimization and the mechanisms associated with placement and compaction using modern materials and equipment. Most studies cited today were done in laboratories more than 20 years ago. They do not take into consideration the market, field conditions, and materials now in use.

Emphasis has been placed on setting broad limits for ingredients, but no effort has been made to quantify the composition of the end products. For a given set of materials, there are many combinations that will produce a given strength and/or water-cement ratio. Which will be compatible with the construction process and assure the needed durability? This question is seldom asked. Instead, only 28-day strength and price are considered.

To get things back on track we must address today’s industry and cope with the conditions as they now exist. There are many excellent new products, processes, and pieces of equipment that can contribute to better quality concrete. Admixtures, fly ash, pulverized slag and silica fume are here to stay.

SLUMP TESTS

Better controlled and finer ground cements, along with advances in chemical admixtures, are resulting in higher early strengths. Because acceptance testing is often based on compressive strength and slump, the effects of increased water-cement ratio have gone unnoticed until structures started deteriorating earlier than anticipated.

The highly regarded slump test should be recognized for what it is: a measure of the ability of a given batch of concrete to sag. Slump has only minimal relationship with strength. It is the ratio of water to cement that affects strength and durability. The amount of water required to produce a constant slump varies based upon factors that are allowed to vary within broad standards. Among those factors that affect water demand are fine aggregate grading, aggregate particle shape and structure, amount of each aggregate in the individual batch, temperature, time in transit, entrained air content and the accuracy with which admixtures are added to the batch.

These things, too, have changed with time. A concrete with a specified strength of 3,000 or 4,000 psi cast at a 4 in. slump today is not the same as concrete cast 30 years ago to produce the same strengths. Cements produced at that time resulted in concrete strength gains of about 25% after 28 days. Today this gain can be as low as 5%. The only things that haven’t changed are the design criteria.

Thirty years ago, a 4,000 psi concrete produced about 4,800 psi at 28 days. Ultimately it attained a strength of 6,000 psi. Engineers who investigate old structures often comment that the strength of cores is amazingly high. To attain ultimate strengths of 6,000 psi today with materials that gain only 5% after 28-day tests, field tests should reach 5,700 psi. Design strength would have to be specified at about 5,200 psi. It was the 6,000 psi strength that controlled durability, not the specified 4,000 psi.

Concrete with a strength of 4,000 psi once required a mixture with a water-cement ratio of about 0.43 to 0.45. Today the same strength is produced with water-cement ratios ranging from 0.51 to 0.54. The 28-day compressive strength per se has little to do with durability.

STATISTICS DON’T HELP

Another factor that effectively reduced in-place strength is the use of statistics. Statistics allow concrete to be used, even though tests of individual batches fall below the specified strength. There is nothing wrong with this procedure. Using mathematical models, the shortcomings of some batches can safely be made up for in other lots. But test results falling below the specified strength were not acceptable 30 years ago. To assure all tests were above 4,000 psi, the average strength produced used to average 4,800 psi at 28 days. Today, 4,000 psi specified strength concrete averages as low as 4,300 psi with good quality control.

This can lead to two possible consequences. A 500 psi reduction in test specimen strength could allow a reduction of about 55 lb of cement per cubic yard or an increase in water. The result is an increase in allowable water-cement ratio to produce a given strength and a reduction in durability.

There are decided advantages to...
statistical control when it is used correctly. It places the responsibility for quality control on the producer. It rewards those with good control and penalizes those with poor control. It can be tracked and it is a part of the building code.

AN ENGINEERING SOLUTION

But it is the engineer who must determine the basis for acceptance. There are two options: concrete can be selected primarily for its load carrying abilities or for its durability. The former can be called "passive" concrete; the latter is "active" concrete.

There is little environmental impact on the performance of passive concrete. It can be evaluated by its minimum strength measured at 28 days and is designed with two barely adequate objectives in mind: constructability and low price. Statistical control is ideally suited for such projects.

Active concrete is concrete that must function under changing conditions and respond to varying environments or abuse. It is generally a part of civil works, though industrial slabs are an example of active concrete in buildings. Performance is based on water-cement ratio rather than load bearing ability. In most cases, the strength to be produced for the durability dictated water-cement ratio will exceed that required for structural loads.

With a water-cement ratio of 0.42, the products of the hydration process almost exactly fill the voids originally filled by the water. As the water-cement ratio increases, the voids increase and durability decreases.

The American Concrete Institute tables for recommended strengths do not take the modern durability needs into consideration. Most were prepared long before changes were made in the materials characteristics. In today's competitive market, it is nearly impossible for a concrete producer to follow water-cement ratio requirements anyway. The solution is for the engineer to specify a strength that, though higher than required for structural needs, the contractor can only meet by using the desired water-cement ratio.

Many specifications include a maximum water-cement ratio and a compressive strength. Often the strength is less than what would be produced if the water-cement ratio were followed. This is tantamount to specifying two different materials and is poor practice. Contract documents often state that the contractor should comply with the most stringent standard. However, in court, practice often outweighs the written word when the written word has not been adhered to in the past. Because of the difficulty in confirming actual water-cement ratio, final judgment is made on the compressive strength. With reasonably good materials and a 0.45 water-cement ratio, strength measured at the point of deposit should be considerably above 6,000 psi.

ON THE ROCKS

Aggregate particle distribution also is important for active concrete subject to abrasion and erosion. Once the surface paste is eroded, it is the aggregate that becomes the wearing surface. Good, hard, dense aggregate wears better than porous mortar.

Engineers, contractors and suppliers need a better, simplified means to understand concrete mixture proportions. This technology affects not only strength and durability but also construction practices, resource conservation and both short- and long-term economics.

Much can be learned from soils engineers and their studies of soils density and asphaltic concrete engineers and their procedures for selecting mixture proportions. Portland cement concrete, roller compacted concrete, asphaltic concrete and stabilized granular soils are closely allied—only the binder and plasticity are different. Concrete mixture proportioning technology is not an art. It is an easy-to-understan science.

The primary mixture proportioning procedures used today predate World War II. The "percent of aggregate" procedure has no technical basis and is an adaptation of volumetric batching before scales were available.

The principles of a good concrete mixture can be compared to a laid-up stone wall. The mason selects the large stones, fills the major voids with smaller stones, and bonds the stones together with mortar. As the number and shape of the smaller particles varies, the need for mortar varies. In concrete, the +1/4 in. particles are the "big" stones. Those that pass the 3/8 in. sieve but are retained on the No. 8 sieve are the fillers, and the minus No. 8 fine aggregate and the paste form the mortar. Stockpile origin is immaterial. It is the com-
bined particle distribution that affects mixture performance.

The wall is static but concrete must be mobile. That requirement, too, is handled by mortars adjustments. Slump adjustments are not enough. Concrete placed by chute in 2 ft of footing needs less mortar than that placed by 4 in. pump in a second floor pan joist slab or an 8 in. wall. Added mortar is necessary not only for the pump line but also to provide a skin for the formed and top surfaces.

Much has been learned about the effects of particle distribution from specially developed computer software, now in use across the U.S. and in many other countries.

The program mathematically combines the ingredients and, through a series of charts, tables and graphs, describes the characteristics of the mixture. From these, the user can evaluate the potential performance of that mixture.

Practically any sound aggregates can be combined to produce a given strength concrete. However, when particles are poorly distributed the mixture can cause both construction and performance problems. When the mason building the laid-up stone wall doesn’t have the smaller stones to fill major voids, he must use more mortar to do the job. It is the same with concrete. A deficiency of particles passing the 1/2 in. but retained on the No. 8 sieve can necessitate use of more mortar. Generally sand and water are added without the additional cement required to keep the water-cement ratio constant.

In most industrial nations and some sections of the U.S., at least three aggregate sizes (two coarse and one fine) are mixed to assure a more consistent particle distribution. The third aggregate is predominately intermediate (1/2 in. to No. 8) size to provide a bridge between the large particles and the mortar, to fill major voids and to increase concrete density. When size 457 (1 1/4 in.) aggregate is specified, three coarse aggregate sizes should be used.

MIXTURE OPTIMIZATION

When aggregate particle distribution is optimized, the concrete density can be optimized. The optimization does three things. Water-cement ratio with a given cement factor can be reduced because voids are filled with aggregate. Resistance to abrasion and erosion also is increased, because dense aggregate becomes a better wearing surface than mortar once the skin is worn away. Finally, the amount of mortar needed to fill voids is reduced, thereby reducing the channels for water and other damaging materials to penetrate the concrete.

The addition of cement and lowering of slump for the sake of reducing water-cement ratio does not assure a durable concrete. If there is an inefficient relationship between a mixture and the compaction equipment, density will be affected. In the worst condition, sharp particles can cause the physical set when aggregate particles interlock. This creates low density and a poor finish.

It may be necessary to increase mortar (fine aggregate, cement, pozzolan or slag, and water) content to maintain a specified water-cement ratio and to overcome problems caused by aggregate particle distribution and shape. If water-cement ratio is the primary influence on durability, two mixtures at the same water-cement ratio (and entrained air) should produce the same results.

Two similar mixtures, for example, might have the same 0.43 water-cement ratio. But the mortar in one accounted for 49% of the volume and the other accounted for 63%. The former, with a better particle distribution, was responsive to vibrators, produced high density, and finished well. The latter was "stickey" and caused placement and finishing problems.

The mortar content of the former mixture was 20% lower than the latter. This means there are 20% fewer channels through which water or deleterious materials can migrate. Dense stone, which is the most durable part of the mixture, replaced the porous mortar. The lower mortar content mixture will be more durable though it contained more than 100 lb less cement per cubic yard. Moisture and airborne deleterious materials can penetrate good, solid stone. To maintain the water-cement ratio constant, more cement and water must be used to satisfy the needs of the added fine aggregate.

At a constant water-cement ratio, slump can be changed as much as 3-4 in. by varying aggregate proportions. The change is based on the water demand for varying quantities of fine aggregate. This suggests that it is possible to increase slump and decrease water-cement ratio simultaneously.

If change is to occur, the engineer must take the lead. The place to start is with specifications. One alternative is to require at least two sizes of coarse aggregate and strengths that relate to the durability vs. load carrying requirements for a project.

The U.S. Army Corps of Engineers has taken a creative approach for roller-compact ed concrete. Its guide specification provides limits for a combined grading for aggregate from 1/4 in. to No. 200 sieve. Once the mixture is selected, the tolerance for variation by each sieve in the combined grading is limited. To the performance oriented specifier, this is an ideal opportunity. Constant pressure to produce consistent aggregate grading meeting arbitrary standards is coming pressure on the natural resources. Some sizes are in short supply while others are being wasted. Mixture performance is based on the combined grading and not the stockpiles.

Typically, mixture proportions are submitted to the engineer for review. Few engineers do more than see that a reasonable cement factor is planned and that the supplier indicates a certain strength will be produced. That is not enough. Engineers must take a more active part in the analysis to verify if the water is properly estimated, the aggregate is appropriate for the work, and the cement factor will fit the temperature conditions for placing. Yes, the contractor has the ultimate responsibility, but jobs run smoother when there are fewer problems. Once an engineer reviews a document, according to the courts, he has a legal responsibility for the results.

The potential for concrete performance has not been reached.

We should be at the end of the "art" era and at the start of "science" in the use of our most versatile building material: concrete.

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Graphical Approach to Mixture Proportioning by ACI 211.1-91

by Ken Hover

ACI's “Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete (ACI 211.1-91)” provides a wealth of information for the mix designer. While the clearly written text and numerical examples walk the designer through the process in a step-by-step manner, the heart of the document is in the tables of mixture proportioning data. Such data may be more clearly and effectively presented as graphs in addition to the tables.

Many people involved in the mixture proportioning process are “graphically oriented” and may be more accustomed to obtaining values from a graph than from a table. Furthermore, the essential advantage of a graph is that it provides not only the numbers, but also shows the underlying relationships. This is of great value in learning and understanding the mix design process. The mix designer who puts together a trial batch based on understanding the relationships is also in a good position to make the necessary adjustments when the trial batch test results are obtained.

Given the variables involved, concrete mixture design is by nature an approximate process. For this reason, ACI Committee 211 has written in Chapter 1 of its 211.1 document: “The methods provide a first approximation of proportions intended to be checked by trial batches in the laboratory or field and adjusted, as necessary, to produce the desired characteristics of the concrete.”

The graphical format suggested here is entirely compatible with the notion of a “first approximation” and, in fact, may be more appropriate than the data tables to which novice mix designers often ascribe a false precision.

Beginning with the following example comparing graphical to tabular data, the ACI 211 data are presented in graphical format, with a brief discussion to draw attention to key features. With the exception of Table 6.3.4(a), reprinted from ACI 211.1-91, no other ACI data tables are shown.

Comparison of tabular and graphical data presentation

Compressive strength as a function of w/c

Consider Table 6.3.4(a), reproduced on the next page, which indicates the relationship between the water-cement ratio (w/c) of the concrete and the average 28-day compressive strength. For comparison, the same data are shown in Fig. 1. It is obvious from the table that strength and w/c are somehow inversely related, and that to achieve any given level of strength a lower w/c is needed for air-entrained concrete. However, Fig. 1 more clearly shows the nature of these relationships. It is observed in the graph that increasing w/c from 0.40 to 0.45, causes a relatively greater reduction in strength than increasing w/c from 0.75 to 0.80. The graph also demonstrates Committee 211’s assumption on the impact of air entrainment at any given value of w/c: for strengths in the range of 6000 psi, air leads to a reduction of close to 1000 psi. For strength in the range of 2000 psi, air leads to about a 500 psi reduction. (The footnote to Table 6.3.4(a) — not reproduced here — indicates that “air entrained” in this case implies a total air content of 6.0 percent.)

Other advantages of the graphical approach have been observed in the author’s experience in teaching mixture proportioning to both college students and practicing professionals: when using the data table the mix designer is more likely to assume an unintended precision for the value obtained. For example, if a 5000 psi (35 MPa), non-air-entrained mixture is desired, the novice mix designer is likely to infer from the table that a w/c of “exactly 0.48” is required. The same designer is more likely to correctly infer that a w/c of “about 0.48” is required when drawing a conclusion from the graph. Similarly, students exposed to graphical data less frequently confused air-entrained for non-air-entrained concrete in the process of selecting the appropriate w/c than did students who were exposed only to the table. Note that in Fig. 1 the data points are taken directly from the ACI 211.1 tables while the curves represent the best fit to those data. Similar curve fitting was done for the balance of the graphs shown.

Supplementary graphs for ACI 211.1

Approximate mixing water

The approximate mixing water requirement or “water demand” is shown in Fig. 2 and 3 for non-air-entrained and air-entrained concrete, respectively. These data are adapted from Table 6.3.3 of ACI 211.1. Another interesting way of looking at these same data is shown in Fig. 4 and 5, in which the
slump (taken as the mid-value of the slump range in Table 6.3.3) is plotted as a function of water content (with water content on the horizontal axis). While ACI tabular data include coarse aggregate nominal sizes up to 6 in. (150 mm), 2 in. (50 mm) is the largest shown in these figures. The influence of using a larger coarse aggregate to reduce water demand is clear.

The curves in Figs. 4 and 5 show an exponential relationship between water content and slump; that is, successive increments of water addition have successively larger influences on slump. This is as observed in practice, not only in the process of mixture proportioning and trial batching, but also in the field. One or two modest additions of water may fail to produce the desired slump, but the next increment of water added turns the mix to soup!

The uncertainty in predicting workability on the basis of water content and aggregate size alone is indicated by ACI in the slump ranges given in Table 6.3.3. While Fig. 4 and 5 indicate only
the mid-value of these ranges. Fig. 6 shows the entire range for non-air-entrained concrete. The dashed lines represent the ACI mid-range points.

**Bulk volume of coarse aggregate**

Fig. 7 shows the bulk volume (fraction) of coarse aggregate, or the ratio of bulk coarse aggregate volume to total concrete volume, sometimes called $b_{0}$. ACI Table 6.3.6 includes data up to a coarse aggregate size of 6 in. (150 mm). The larger the coarse aggregate size, the more it can be used in the concrete mixture (with the beneficial effect on water demand as seen earlier).

The effect of the fineness modulus of the sand is seen as well, where coarser sand requires a bit more room in between the coarse aggregate particles, and therefore reduces the bulk volume fraction slightly.

**Required air content**

Fig. 8 shows both ACI data points and smooth-fitted curves for the recommended air content as a function of nominal maximum aggregate size and freeze-thaw exposure. As the aggregate size increases, the required air content decreases, which is a consequence of the generally decreasing paste and mortar content in mixtures with larger coarse aggregates. Multiple footnotes to the ACI table provide additional information.

**First estimate of weight of fresh concrete**

Fig. 9 demonstrates the impact of increasing coarse aggregate size and air entrainment on the estimated weight. (Correction factors for this data are in ACI 211-91.)

Note that as nominal coarse aggregate size increases (and paste content decreases per Fig. 6), the density of the mixture increases as well—assuming dense, normal weight aggregate.

**Derivative and composite graphs**

Beginning with the basic relationships shown so far, any number of graphs can be drawn that derive the information on the basis of the ACI 211 procedure.
or that combine data from several graphs. For example, Fig. 10 derives the required cement content from the previously and independently determined water content and w/c. (Cement content is determined by dividing the water content by the w/c; strength and workability are independently determined; see ACI 211.1-91, Chapter 6).

Fig. 11 is a composite of Fig. 5 and 10. In it, the cement content is determined as a function of the maximum nominal coarse aggregate size, slump, and desired w/c for air-entrained concrete. A similar composite graph is shown in Fig. 12 for non-air-entrained concrete, in which two mixes are shown, both with a planned slump of 3.5 in. (89 mm). In one case a 3/4 in. (19 mm) coarse aggregate is used that requires a water content of about 340 lb/ft³ (200 kg/m³). If a w/c of 0.50 is desired, the required cement content will be about 690 lb/ft³ (410 kg/m³).

For the alternate case of the same slump and the same required w/c, a choice of a 1.5 in. coarse aggregate (38 mm) leads to a required cement factor of about 600 lb/ft³ (360 kg/m³). In this example, increasing the coarse aggregate size effectively reduced the water content and cement factor by about 13 percent. To maintain workability the mix designer would have to make sure that the total aggregate gradation was properly balanced.3

**Discussion**

Of the multiple potential advantages to graphical presentation of mixture proportioning data, perhaps the most important is that the underlying relationships become clearer to those who are accustomed to interpreting graphic data. As pointed out by Sandor Popovics,1 the data could be made even more accessible to some people by including the mathematical equations that de
scribe each of the curves. Such equations are the basis for many computer mixture proportioning routines. As seen in the graphs, the SI conversions are easily performed, and the notion of "approximate" results without false precision is reinforced.

Finally, the graphical presentation of mixture proportioning data is not a new idea, with precedents within ACI technical publications as well as within the international literature (References 4, 5, and 6, among others). It may therefore be useful for ACI’s mixture proportioning committee to consider adding graphs in an upcoming revision to their excellent series of documents.

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Fig. 10 — Approximate cement factor as a function of w/c and water content.

Fig. 11 — Cement factor and slump as a function of w/c and water content for air-entrained concrete.

Fig. 12 — Cement factor and slump as a function of w/c and water content for non-air-entrained concrete.