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

Concrete Mixture Optimization

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:

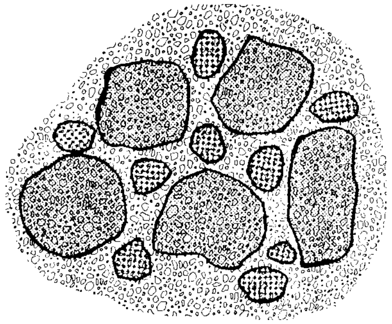

Fig. 1 — Well graded mixture.

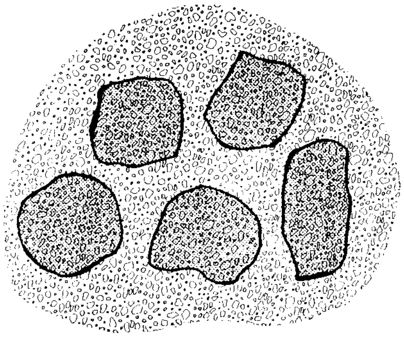

Fig. 2 — Gap graded mixture.

Keywords: aggregate size; **concretes;** costs; **mix proportioning;** mortars (material); **optimization;** particle size distribution; performance; quality control; standards.

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*ASTM now recognizes this problem and a task group has been set up to introduce a revision that will provide for combined aggregate gradings in addition to coarse and fine aggregate gradings.

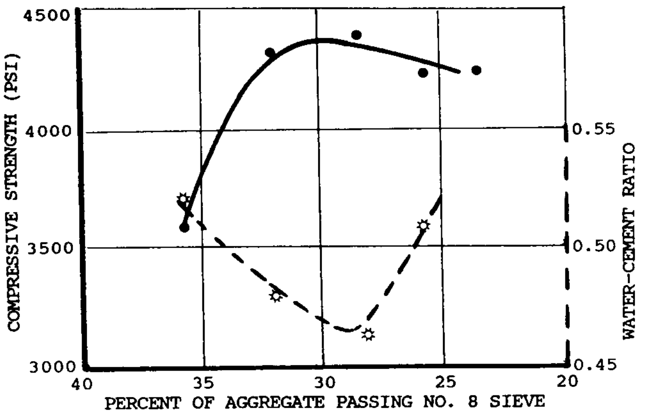

Fig. 3 — Fine sand vs. strength and water-cement ratio.

Table 1 — Aggregate characteristics.

	Wadi Gravel			Quartz sand
	A	B	Blend	
Sieve size	Percent passing sieve size			
1 in.	100	100	100	
¾ in.	95.5	100	96.4	
½ in.	54.0	100	63.2	
⅜ in.	17.0	90.5	31.7	100
#4	2.9	32.8	8.9	100
#8		2.6	0.5	99.1
#16		0.6	0.1	96.2
#30				71.0
#50				17.0
#100				4.0
SG*	2.70	2.70	2.70	2.64
FM**				2.13
DRUW*** (lb/ft^3)	100.4	101.2	102.5	
Absorption (%)	1.0	1.0	1.0	1.0

*Specific gravity **Fineness modulus ***Dry rodded unit weight

- 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 this 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 placable 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

Table 2 — Trial mixture data, Athens tests.

Mix data		Initial Tests					Architectural	
% of DRUW*		75	81	86	90	93	83	86
Coarse Aggregate	%	63.3	68.0	71.8	74.6	76.6	69.8	71.8
Cement	lb	564	564	564	564	564	564	564
Fine Aggregate	lb	1175	1035	920	835	775	975	920
Coarse Aggregate	lb	2075	2240	2380	2490	2575	2300	2380
Water	lb	292	272	260	287		293	304
Admixture	oz	23	23	23	23	23	23	23
w/c		0.52	0.48	0.46	0.51		0.52	0.54
Slump	in.	2.25	3.0	2.0	2.0	2.25	2.5	2.0
Compressive strength (psi)	7-Day	2650	3080	3400	2870	3110	3600	3080
	28-Day	3588	4303	4393	4222	4233	4680	4647

*Dry rodded unit weight

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.

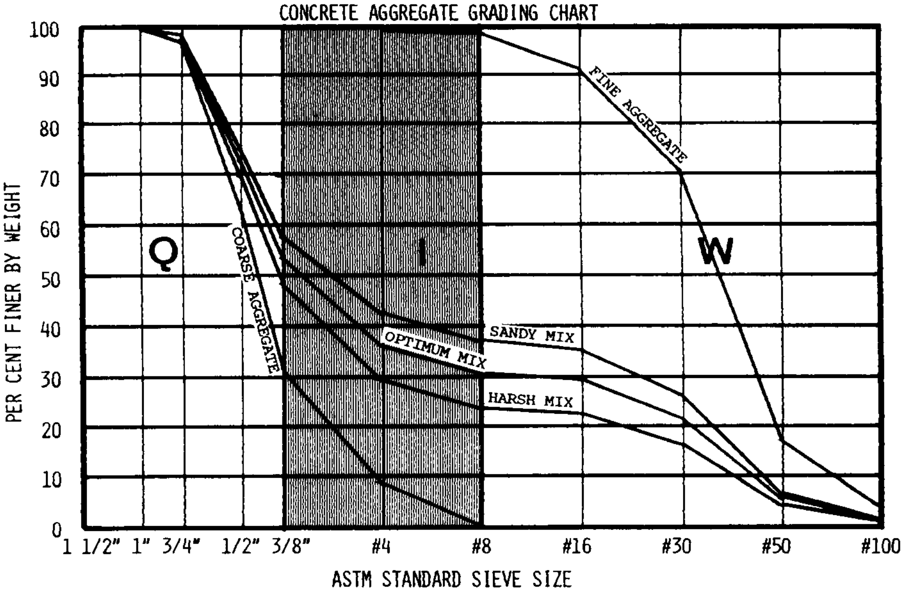

Fig. 4 — Combined aggregate gradations.

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 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 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 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.

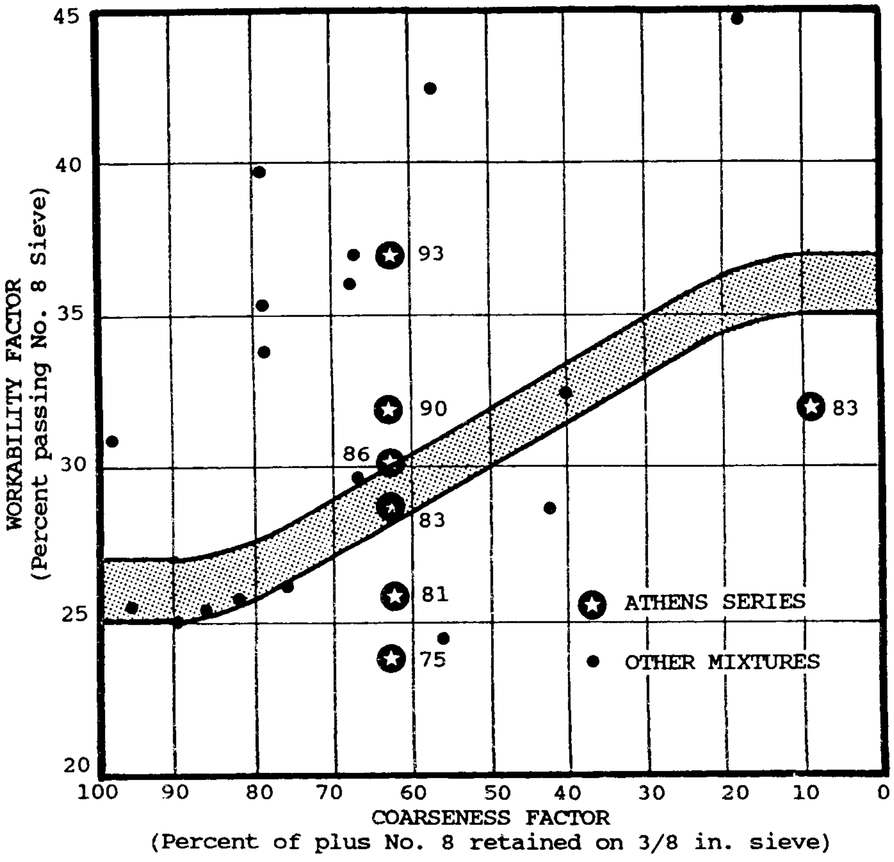

Fig. 5 — Coarseness factor chart.

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 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 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 crazing 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 [255.8 kg]) of cement. At that factor *W* and *W-Adj* are identical. As cement factors vary from 564 lb (255.8 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.[2]

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/yd' (20 kg/m'). 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 by chute 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 joist slabs, thin or small castings, and high reinforcing 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.

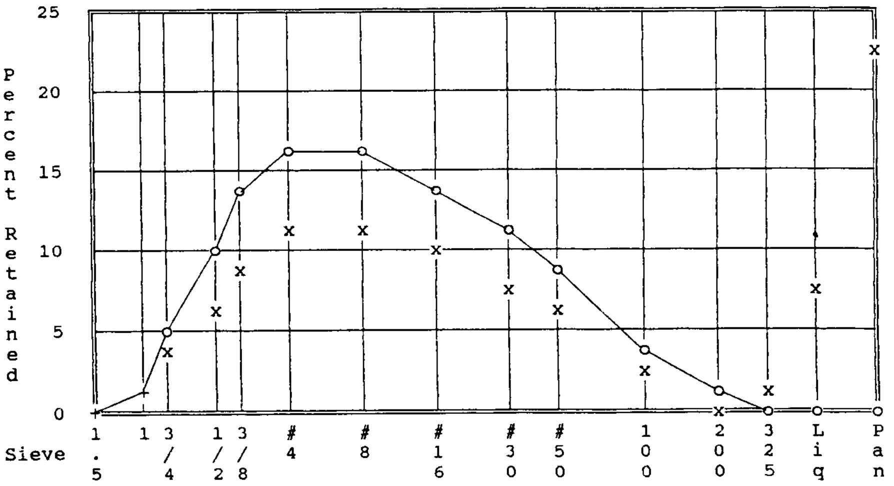

Fig. 7 — Optimum graded mixture.

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 3/8 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 over-mortared 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 (3/8 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-

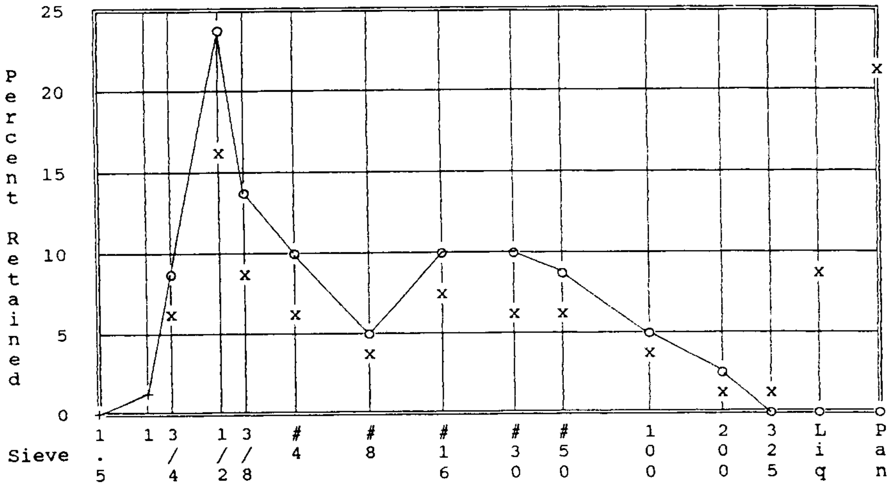

Fig. 6 — Near gap graded mixture (1988 ASTM C 33).

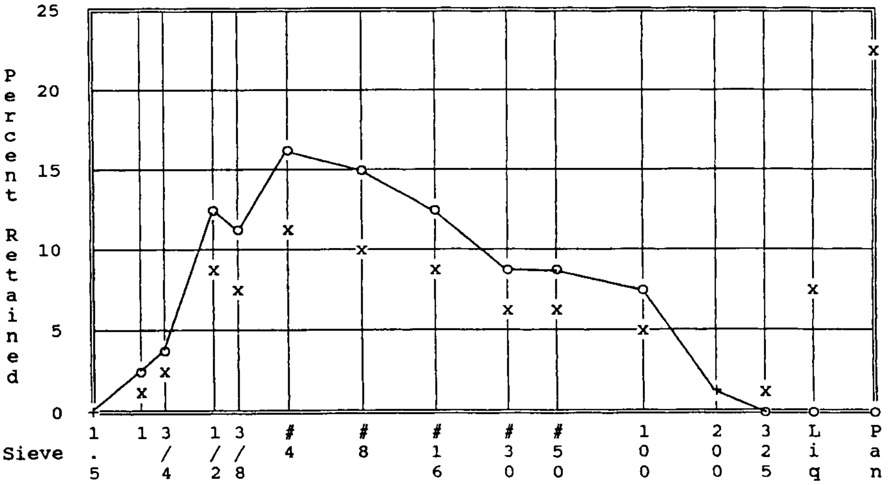

Fig. 8 — Combined gradation (1923 ASTM C 33).

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 ½ 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 (3/8 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 (1½ 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 pea gravel 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 definitive 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.

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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 1979 and the Construction Practices Award in 1987.

OPTIMIZING BY THE 0.45 POWER CHART

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 a 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 stockpiles 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, on 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 Coarseness 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.