Quality-Assurance System for Cement-Aggregate Concrete

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The concrete construction industry is unique because it involves quality-control systems that must be exercised on the production and performance of individual materials (cement and aggregate) and also of concrete, the ultimate product in which these materials are used. Therefore, specifications written for one material will generally affect the performance and ultimate consumer cost of all three materials because of the degree of quality control required for each material. To demonstrate the effect specifications may have on the ultimate cost to the consumer, examples from a concrete supplier's quality-control and quality-assurance program are presented. The equipment and manpower required for carrying out these programs and the ultimate effect of these requirements on the economics of product processing are described.

Prior presentations have dealt with the significant aspects of quality-assurance programs for individual components. As a producer of cement and other building materials, we are keenly aware of the problems associated with the production of these components. As a supplier of these materials to the construction industry, we have likewise been keenly aware of the performance requirements necessary to make these products acceptable in the marketplace. For this reason, we look at quality-assurance programs from a broader viewpoint. The relation between the components and the system plays a significant part in our ability to produce a quality product that can be sold competitively in the marketplace.

Techniques for quality control have been consistently improved through the years. Improved production, process control, monitoring, testing, and data processing equipment and techniques have been the basic factors in our ability to establish new process and product performance standards. In cement plants, for instance, quality-control systems control and monitor the functions of quarrying, proportioning and blending at two stages, raw grinding, burning and cooling, finish grinding, and storing and withdrawing cement. For each function, specific sampling and control testing procedures are carried out and documented. Our particular control system involves almost 23 000 man-hours of work annually. Backup technical assistance involves at least 10 000 man-hours of work by our research laboratory personnel.

Depending on the degree of sophistication built into the system control, the data are collected, recorded, and analyzed either manually or automatically through the use of computers for maintaining control over the operating parameters. In addition to the traditional cement-testing equipment, X-ray, atomic absorption, DTA, microscopic, and mineralogical tests are also conducted.

A diagram of the cement process flow and the quality-control function exercised at various stages is shown in Figure 1. We have established separate standards for each production phase. In effect, each department has its own quality-assurance or quality-control program. Standard deviations and coefficients of variation have been the basic statistical tools for evaluating the variations in the chemical and physical properties of the cement. The control data and graphics shown in Figure 2 are used for visual-trend studies. At each plant, quality-control personnel observe these trends and are responsible for controlling them.

In the aggregate industry, we have similar controls over the production process with particular emphasis on size reduction (crushing), beneficiation, and size gradation. For concrete, the emphasis is placed on the proper blending of materials of a given quality so that a concrete of a defined quality is produced.

Concrete control data and graphics, similar to those based on the American Concrete Institute (ACI) code, are prepared. Examples of such information are shown in Figures 3 and 4. Our desire is to maintain a low standard deviation from the norm. We believe that greater flexibility can be allowed in specifications without sacrificing quality standards.

To further strengthen these quality-assurance procedures, test programs are established to evaluate the testing personnel and equipment, since the evaluation concerns the testing agreement between testing laboratories and testing personnel. Many laboratories, like ours, are certified by the Cement and Concrete Reference Laboratories of the National Bureau of Standards.

Therefore, quality-assurance programs for individual

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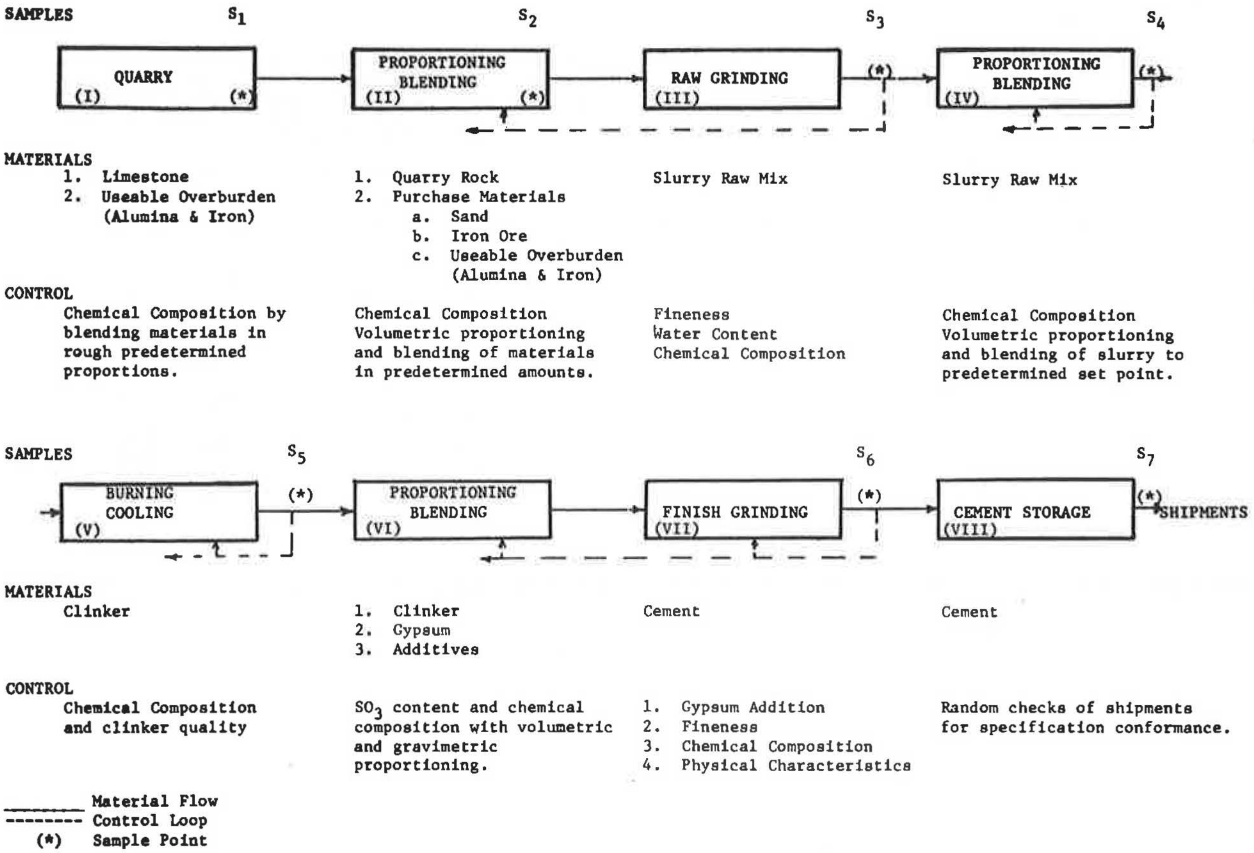
Figure 1. Quality-control systems for process flow, sampling, and control loops.



	(I) Quarry	(II) Proportioning Blending	(III) Raw Grinding	(IV) Proportioning Blending
MATERIALS	1. Limestone 2. Useable Overburden (Alumina & Iron)	1. Quarry Rock 2. Purchase Materials a. Sand b. Iron Ore c. Useable Overburden (Alumina & Iron)	Slurry Raw Mix	Slurry Raw Mix
CONTROL	Chemical Composition by blending materials in rough predetermined proportions.	Chemical Composition Volumetric proportioning and blending of materials in predetermined amounts.	Fineness Water Content Chemical Composition	Chemical Composition Volumetric proportioning and blending of slurry to predetermined set point.

	(V) Burning Cooling	(VI) Proportioning Blending	(VII) Finish Grinding	(VIII) Cement Storage
MATERIALS	Clinker	1. Clinker 2. Gypsum 3. Additives	Cement	Cement
CONTROL	Chemical Composition and clinker quality	SO_3 content and chemical composition with volumetric and gravimetric proportioning.	1. Gypsum Addition 2. Fineness 3. Chemical Composition 4. Physical Characteristics	Random checks of shipments for specification conformance.

Figure 2. Computerized production analysis report of type 1 cement.

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                                                        * CHEMICAL ANALYSIS *

                                                                                           C2F              FREE    INS                    T    NO
  MONTH      SIO2  AL2O3 FE2O3   CAO    MGO    SO3   LOSS TOTAL    F    R    A/F  C3S  C2S  C3A C4AF CASO4   CAO    RES   NA2O     K2O  ALK  ISI
JULY       *21.71  5.08  2.31  64.72  1.05 *2.96  1.14  99.0  2.46 2.94 2.20 52.6 22.5  9.6  7.0  5.0    .67    .42   .09     .72  .56 19
AUGUST      21.42  5.10  2.31  64.53  1.09  3.22  1.35  99.0  2.48 2.89 2.21 53.2 21.3  9.6  7.0  5.5    .72    .38   .10     .73  .58 17
SEPTEMBER   21.33  5.09  2.26  64.63   .95  3.27  1.43  99.0  2.49 2.90 2.25 54.2 20.2  9.7  6.9  5.6    .79    .47   .10     .74  .59 30
OCTOBER     21.33  5.05  2.41  64.67  1.06  3.28  1.25  99.1  2.49 2.86 2.10 54.4 20.0  9.3  7.3  5.6    .63    .30   .11     .77  .62 23
NOVEMBER    21.40  5.04  2.38  64.52  1.06  3.31  1.11  98.8  2.48 2.88 2.12 53.3 21.1  9.3  7.2  5.6    .48    .29   .10     .78  .61 14
DECEMBER    21.26  5.06 *2.55 *65.00   .99  3.21   .96  99.0  2.52 2.79 1.98 56.2 18.5  9.1  7.8  5.5    .46    .43   .11     .76  .61 11
JANUARY     21.26  5.12  2.44  64.87   .97  3.24  1.16  99.1  2.51 2.81 2.10 55.4 19.1  9.4  7.4  5.5    .47    .43  *.15     .76  .65  7
FEBRUARY    21.25  5.14  2.38  64.65  1.03  3.31  1.15  98.9  2.50 2.83 2.16 54.3 19.9  9.6  7.2  5.6    .63    .40   .11     .77  .62  9
MARCH       21.34  5.06  2.46  64.76  1.13  3.27  1.06  99.1  2.50 2.84 2.06 54.6 19.9  9.2  7.5  5.6    .41    .36   .07     .73  .55 11
APRIL       21.30  5.09  2.41  64.67  1.19  3.24  1.14  99.0  2.50 2.84 2.11 54.5 19.9  9.4  7.3  5.5    .46    .33   .07     .71  .54 18
MAY         21.31  5.09  2.30  64.72  1.19  3.27  1.20  99.1  2.50 2.88 2.21 54.7 19.8  9.6  7.0  5.6    .52    .37   .08     .72  .55 18
JUNE        21.31 *5.23  2.37  64.57  1.17  3.25  1.30  99.2  2.48 2.80 2.21 53.1 21.0  9.8  7.2  5.5    .50    .38   .08     .76  .58 14


HIGH        21.71  5.23  2.55  65.00  1.19  3.31  1.43  99.2  2.52 2.94 2.25 56.2 22.5  9.8  7.8  5.6    .79    .47   .15     .78  .65
LOW         21.25  5.04  2.26  64.52   .95  2.96   .96  98.8  2.46 2.79 1.98 52.6 18.5  9.1  6.9  5.0    .41    .29   .07     .71  .54
AVERAGE     21.36  5.09  2.36  64.67  1.07  3.23  1.22  99.0  2.49 2.87 2.16 54.1 20.4  9.5  7.2  5.5    .59    .38   .10     .74  .59

STD.DEV.      .12   .05   .08    .11   .08   .09   .13    .1   .01  .04  .07   .9  1.0   .2   .2   .2    .12    .06   .02     .02  .03

                                                        * PHYSICAL ANALYSIS *

              FIN                     V-I-C-A-T    G-I-L-M-O-R-E   FALSE   NORM              AIR     COMPRESSIVE STRENGTH     AUTO   NO
  MONTH      #325   WAGNER  BLAINE   INIT  FIN     INIT     FIN      SET   CONS     %H2O    ENT   1DAY  3DAY  7DAY 28DAY   CLAVE   ISI

JULY         86.2    1785    3300     85   180     2.20     4.15      88   25.0     48.5    11.0   1950  3240  4230  5410   .005    19
AUGUST       85.1    1780    3275     80   175     2.20     4.15      65   24.5     48.5    11.4   1965  3275  4125  5245   .001-   17
SEPTEMBER    87.3    1875    3535     75   175     2.10     4.10      82   24.5     48.5    11.2   2090  3380  4270  5565   .003-   30
OCTOBER      86.3    1855    3290     75   175     2.15     4.15      87   24.5     48.5    11.8  *2260  3510  4450  5485   .008    23
NOVEMBER     87.2    1820    3315     80   180     2.15     4.10      86   24.5     48.5    11.1   2075  3420  4300  5490   .010-   14
DECEMBER     86.9    1770    3180     85  *190     2.25     4.15      84   24.5     48.5    11.5   2130  3370  4365  5400   .012-   11
JANUARY      86.7    1810    3145     80   180     2.15     4.10      86   24.5     48.0    11.7   2080 *3555  4350  5525   .002-    7
FEBRUARY     85.4    1730    3230     80   175     2.15     4.15      85   24.5     48.5    10.8   2090  3290  4215  5395   .002-    9
MARCH        83.8   *1705    3210     75   175     2.20     4.15      88   24.5     48.5    11.1   1945  3195 *4025 *5030   .002-   11
APRIL        84.4    1780    3265     85   172     2.25     4.15      83   24.0     48.5    11.3   1910  3315  4280  5491   .015-   18
MAY          84.8    1870    3370     85   175     2.20     4.15      88   24.0     48.5    11.2   1940  3330  4245  5276   .017-   18
JUNE         86.1   *1950    3369     83   176     2.15     4.12      83   24.3     48.5    10.9   1920  3287  4323         .018-   14


HIGH         87.3    1950    3535     85   190     2.25     4.15      88   25.0             11.8   2260  3555  4450  5565   .008
LOW          83.8    1705    3145     75   172     2.10     4.10      82   24.0             10.8   1910  3195  4025  5030   .018-
AVERAGE      85.9    1824    3321     80   176     2.17     4.13      85   24.4             11.2   2034  3348  4271  5410   .005-

STD. DEV.     1.1      59     108      4     4      .04      .02       2     .3               .3    111    94   103   141   .008

* VALUES WHICH EXCEED THE AVERAGE BY MORE THAN TWO STANDARD DEVIATIONS
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Figure 3. Computerized concrete quality-control report.

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CONCRETE QUALITY CONTROL REPORT

PROJECT                                                           SPECIFIED 28 DAY STRENGTH   4,000 (10)
CONTRACTOR                                                        CEMENT TYPE   LONE STAR I   LB/CU YD    564 (6SK)
ARCHITECT                                                         W/C   5.25G/SK .47/WT   AGGREGATE 1" GRAVEL
ENGINEER                                                          ADMIXTURE: A-E   NONE   OZ/SK      OTHER 3OZ POZ
SUPPLIER                                                          1905 GRAVEL/YD, 1336 SAND/YD

                            SLUMP                       % AIR                 7 DAY STRENGTH       28 DAY STRENGTH

                    TEST     MOVING             TEST     MOVING           TEST   MOVING          TEST   MOVING
  DATE              VALUE    AVE 3              VALUE    AVE 3            VALUE  AVE 3           VALUE  AVE 3

04-11-73             4.75                                                  4545                   6320
04-12-73             3.75                                                  4570                   5650
04-13-73             4.00     4.17                                         3150   4121            4635   5535
04-20-73             5.25     4.33                                         4315   4045            5255   5180
04-24-73             4.50     4.58                                         4605   4023            5615   5168
04-25-73             5.25     5.00                                         4305   4408            5160   5343
04-26-73             5.00     4.92                                         4395   4435            5800   5525
04-27-73             3.75     4.67                                         3430   4043            4845   5268
04-30-73             4.00     4.25                                         4810   4211            6270   5638
05-01-73             4.75     4.17                                         3785   4008            4990   5368
05-09-73             2.75     3.83                                         4505   4365            5330   5530
05-11-73             5.00     4.17                                         3995   4095            5605   5308
05-15-73             5.25     4.33                                         4505   4335            5905   5613
05-16-73             4.75     5.00                                         4155   4219            5280   5597
05-17-73             4.25     4.75                                         4040   4233            5475   5553
05-18-73             5.00     4.67                                         3510   3901            4200   4985
05-22-73             4.50     4.58

02-28-74             5450   5340    110   5395   5735            5224
02-28-74             4700   4550    150   4625   5297            5218
03-05-74             4520   5100    580   4810   4943            5214
03-05-74             5080   5110     30   5095   4843            5213
03-08-74             4620   5040    420   4830   4912            5209
03-08-74             5070   5360    290   5215   5047            5209

HIGH                                      6535   6247
LOW                                       3620   4077
RANGE                                     2915   2169


NO OF TESTS                                101
AVERAGE                                   5209
STAND. DEVIATION                           606
COEF. OF VAR.                             11.6

AVE. RANGE                                 274
WITHIN TEST STAND.DEV.                     243
WITHIN TEST COEF.OF VAR.                   4.7

APPROXIMATELY  2.3% OF THE TESTS ARE EXPECTED TO FALL BELOW THE DESIGN STRENGTH OF 4000
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components are already in effect. Primarily, they are designed to provide the producer and consumer with a system by which process control and product quality optimization can be measured and cost reduction can be realized. These programs do, however, require many man-hours, sophisticated test equipment, and computerization.

However, is the quality-assurance system itself optimized? Does it assure that the most favorable quality and cost conditions under specific circumstances are realized? Or, are quality-assurance systems for individual components compatible with the objective of the ultimate quality-assurance system that requires a combination of several related systems? Too often, we zero in on one condition and perhaps later on we find we are headed in the wrong direction.

Within our construction-related activities such optimization is difficult to achieve. What are the variables that affect our quality-assurance systems and that relate to quality and cost control? Some of these are type and source of raw materials, type and availability of fuels, processing machinery and equipment, control and test equipment, type and cost of transportation, placing equipment, personnel, and specifications or design criteria. Each of these items obviously plays an important part in establishing the ultimate product quality and the cost of the product.

Some quality-control experts say that one should never consider cost when establishing criteria for optimum quality of the product. For this discussion, we will consider these factors jointly. Usually, there are many ways to achieve the same objectives; therefore, we must ask some basic questions. To what degree is the ultimate use of the concrete product flexible in chemical and physical performance characteristics? What do the specifications allow? To what degree can chemical and physical characteristics of each product (cement and aggregate) vary without affecting the performance criteria of the concrete? What flexibility can be allowed in processing, transporting, and placing without affecting the performance criteria? I have stressed flexibility rather than rigidity because we think a quality-assurance program should have flexibility.

Obviously, these questions indicate the need for correlation analysis. The chemical and performance characteristics of each component must be correlated with the chemical and performance characteristics of every other component to determine what variables have the greatest impact on achieving the ultimate objective, and how the variables can be controlled. Otherwise, ill-conceived quality-assurance programs may be too costly and cumbersome to maintain.

The programs often call for control efforts and information that have an insignificant effect on the final objective and are costly. Mainly these efforts include what we might call cookbook criteria such as organization structure, job descriptions, and internal plant communication forms. Do such requirements make the con-

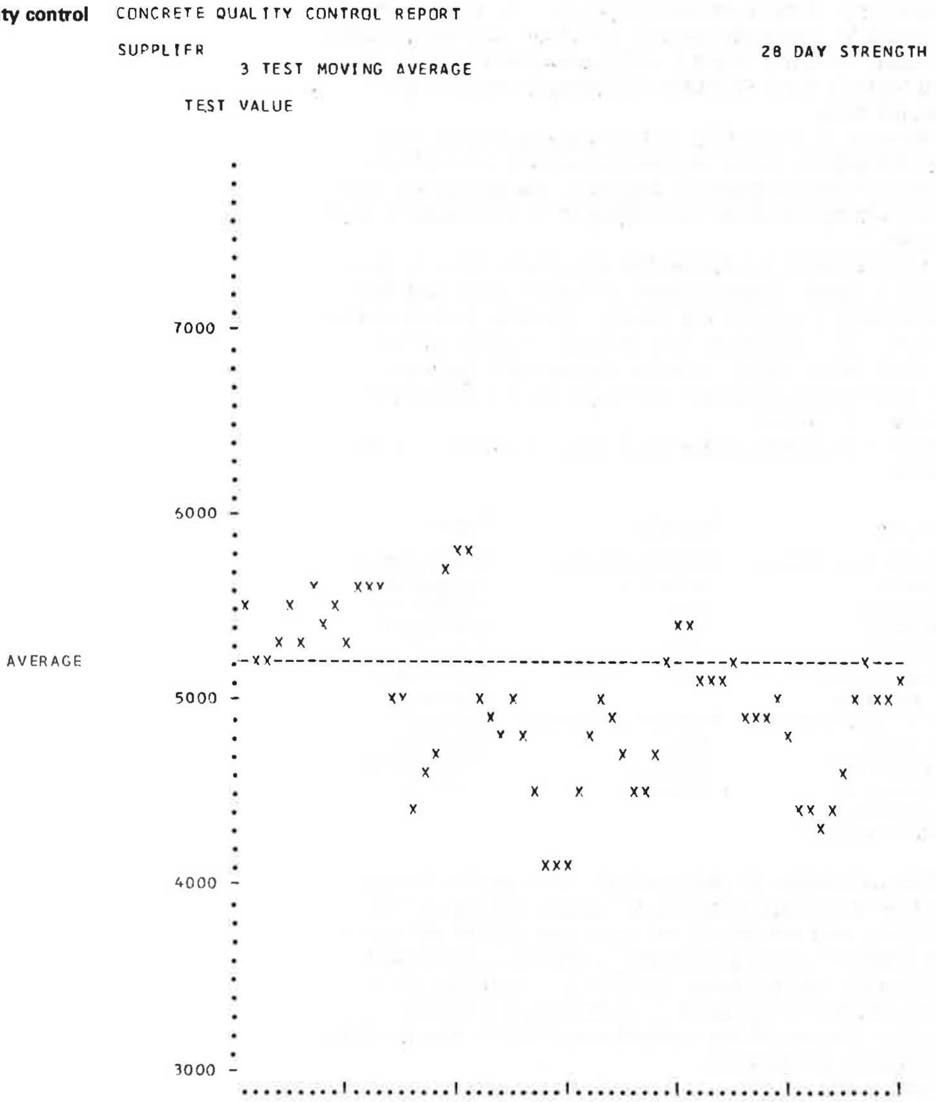

Figure 4. Computerized graph for quality control of concrete.

crete better achieve the performance objectives, or do they perhaps cause us to miss some of the more important points?

While reviewing the cement and aggregate requirements for highway construction in our marketing areas several years ago, we found that most of the states would call for AASHO standard specifications and then add specific exceptions to the specifications for use in their own areas. At that time, we were sure that each state had a legitimate reason for adding other restrictions to ensure product quality and desired field performance. However, as control and evaluation techniques are improved, the need for added restrictions is no longer supported by fact. Today, the need for the costly practice of silo testing and sealing has virtually disappeared. Inventory, sampling, and testing costs were reduced for all parties without sacrificing quality control.

The experience with aggregate is similar. There were 215 dissimilar coarse aggregate gradations specified throughout the United States. AASHO specifications called for 19 gradations. However, in this case, the flexibility of state specifications was based on local aggregate availability and on the knowledge that, although the gradation was different, its impact on the ultimate desired quality of the concrete was not significant.

Quality-assurance programs should, therefore, be structured to primarily flag those characteristics that have a significant impact on product performance, product costs, and placement costs.

It is now possible through the use of computer techniques to make the necessary correlation analysis to determine the critical characteristics that have a significant impact on the ultimate performance and cost of the products. One of the best examples of such a correlation effort is found in the three-part Building Science Series (1). We suggest a similar method for correlating product performance interrelations, concrete performance interrelations, and finally the performance interrelation between both. Initially, this would be a tremendous task because of the many variables that would have to be considered. However, this task would not be impossible. We should first determine what the high-risk, high-cost factors are.

Alkali in cement and aggregate is an important factor. Quality aggregates will become in short supply in many areas. Environmental considerations and raw material availability are influencing the level of alkali in cement. Historical data indicate that cement alkali should be low when used with an alkali-reactive aggregate.

As a result of several specific case histories in which low alkali may have been required, we now find a general demand for low-alkali cements in many areas where its use would have no significant effect on the purpose or performance of the concrete produced. In other areas, the available aggregate or crushed stone may not require low-alkali cement. Good quality-assurance programs would build in such flexibility by using historical performance facts.

Fineness of cement is another area of controversy. Some demand a coarse cement and others demand fine cement for better strength; however, the actual supporting correlation data are not available to substantiate such demands.

I have already mentioned the numerous sizes of gradation required. Suppose each gradation used with the same cement produced the desired strength and durability required. Would the specific gradation specifications have been necessary? A properly designed quality-assurance program would determine if such flexibility could be acceptable.

Some of the criteria for each component relate to the following:

Cement

- Chemical composition
  - Silicates
  - Aluminates
  - Alkalies
  - Sulfates
  - Rare element impurities
- Physical characteristics
  - Fineness
  - Setting time
  - Workability
  - Strength
  - Volume change

Aggregate

- Chemical composition
  - Limestone
  - Basalt
  - Slag
  - Gravel
  - Sand
- Physical characteristics
  - Size
  - Gradation
  - Soundness

Concrete

- Cement content
- Aggregate content and size
- Sand content and size
- Water content
- Admixtures
- Setting time
- Workability
- Volume change
- Durability

This list makes it obvious that, if we are to design a quality-assurance program to satisfy the hopes that variability will not occur, we must use all the information available from producers, testing agencies, and laboratories and put them together in a well-designed quality-assurance program. Certainly, even these variables are not all the variables related to the chemical and physical properties.

Has anyone conducted a correlation analysis based on the performance characteristics of these three components? Such analyses have to be conducted to determine what significant effect the variables of the components will have on the ultimate concrete. Has anyone also considered the intercomponent relations to the concrete performance? We feel the industry or specification writers still have an important step to take before establishing the true relation of each variable to the final product. We may well find that some of our specifications, as written, could be made more flexible and still protect the consumer. At the same time, producer and user would realize significant cost savings in mineral resource conservation, energy requirements, and capital costs. Quality-assurance programs need not be cumbersome or costly to protect the consumer and still minimize process and product costs.

REFERENCE

1. Interrelations Between Cement and Concrete Properties. National Bureau of Standards, U.S. Department of Commerce, Series 1, 2, and 3, 1965-1968.