responsive to a program that is simple to administer and that keeps costs down.

Producer-managed quality control and product certification have proved to be effective methods of improving product quality and reducing inspection and testing costs. Vulcan believes that quality control can be an effective cost control activity and that it will, if properly administered, bring a profitable return to the company on its investment.

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Process Quality Control in the Crushed-Stone Industry

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Selected producers of crushed stone were surveyed on their attitudes toward setting up structured quality control systems that might largely replace much of the conventional testing of aggregates by state inspectors. Their responses are summarized. The overall response was clearly in favor of the concept. Most producers felt that such a system would eliminate many problems and pay off in terms of customer confidence. The essentials of workable, statistically valid specifications that would be appropriate to the producer control concept are outlined. Such specifications should define acceptable variations from approved target gradations for given end uses but should permit considerable latitude to the producer in establishing the target gradation. Good gradation control requires careful processing; the desired consistency is seldom if ever found in materials taken from natural deposits with little or no processing. The importance of close adherence to sound, standardized sampling techniques is emphasized. Both process control samples and samples monitored by state or other agencies should be taken from the "as-produced" material. Test portions for monitoring should be split from routine process control field samples to provide a valid statistical comparison of the producer's control program.

The crushed-stone industry is clearly in favor of specifications based on concepts that recognize the fact that bulk materials are inherently variable and that place realistic limits on the degree of variability that is acceptable. The old, outmoded practice of acceptance or rejection is no longer used in most areas of the country. Specifications must define reasonable limits within which the great majority of quality measurements should fall. However, in view of the many sources of variation in test results, it is unrealistic to expect every sample to "pass" in all respects.

Specifications should also require a measurable degree of consistency in gradation. The old axiom, "We can use a wide variety of gradations, but we cannot tolerate too much variation," should be recognized. This is more important in some end uses than in others.

Specifications for crushed-stone base material, similar in principle to ASTM D 2940, exemplify this concept. They establish a rather wide master range and give producers considerable leeway in selecting a gradation that best fits their operations but require a job mix formula that places more strict limits on deviations from the target gradation selected.

Consistent gradations are important in the case of aggregate base materials, which rely on good compaction and accurate measurement of compaction for maximum load-supporting power. They are extremely important in the case of bituminous mixtures, where variability may affect not only compaction but also void content, both of which strongly influence stability and durability, and in the case of portland cement concrete, where variability may affect water demand to achieve a given slump and thus also affect strength and yield. But in none of these cases is it necessary to require that every aggregate producer who bids on a given job meet a single, narrow gradation band.

Commercial producers of aggregate have found that good quality control programs pay off in a number of ways, especially in producing aggregates to meet this type of specification. Because they produce aggregates that are consistent in gradation and other important characteristics, their products are sought and are more readily accepted by contractors who work in the private sector and for public agencies. In recognition of the fact that crushed stone is generally processed under good quality control procedures, a number of state agencies are reducing their emphasis on sampling and testing of stone by state personnel. The growing tendency is to place greater reliance on the producer's quality control records as the basis for routine acceptance.

On learning that the Federal Highway Administration (FHWA) has been pursuing research in its federally coordinated program (FCP) to "promote the takeover by producers of the job of process control" and thus relieve state inspectors of much of their testing load (1), the National Crushed Stone Association (NCSA) undertook a survey of its members to determine the attitude in the industry toward such a development. The membership was advised that a shift from state test data to producers' data as the basis for quality assurance might involve making available to the state all quality control records on the specified materials. The following sections summarize the responses from NCSA member companies.

SURVEY OF INDUSTRY ATTITUDE

Members of NCSA represent a wide range of company sizes as well as quarry sizes. At some quarries, highly sophisticated plants may be found that are designed to produce annually millions of megagrams of stone of a wide variety of sizes and blends. Other quarries are operated only intermittently, and portable plants are moved in and out to produce just enough material for a specific project or a year's supply of maintenance stone. With very few exceptions, all members who responded to the survey showed a favorable attitude toward the concept of producer control as the basis for quality assurance. Some, in fact, urged that this paper reflect an NCSA policy of actively promoting the concept although this policy has not been formally adopted by NCSA.

Statements of this sort characterize typical responses to the survey:

1. It is good business to make our test data available to our customers, both public and private.
2. This company has maintained its own quality control system for 12 years, and it has resulted in minimal rejection. We are highly in favor of making reasonable reports to various agencies to facilitate acceptance.
3. Preacceptance of stone at the source should add value to offset the cost of a quality control program.
4. Though the cost of quality control is significant, benefits are well worth the cost in terms of customer confidence, up-to-the-minute information on "how well we are doing," and the ability to pinpoint and solve problems.
5. In a state that has used producer control as the basis for acceptance since early 1975, the system has not hurt small operators.
6. We favor the system as described if it is confined to routine gradation and wash-loss tests. Abrasion and soundness testing is still best done by the state.
7. The system would offer no problems if acceptance were granted at the plant or plant stockpile before the material passed from the producer's control. The cost of the system can be determined, but the results may be intangible.
8. Costs should be recoverable even in the private sector. NCSA should assist local associations in establishing workable systems that are not burdened by too much bureaucratic paperwork.

Minority responses to the survey took the following tone:

1. The present system is preferable. Our company furnishes very little stone for highway construction. We doubt that a company quality control system could be justified.
2. We would object to more government intrusion into company operations and question whether the system would eliminate overlapping inspection by state, county, and city representatives.
3. A producer-operated system would be acceptable for specified items. We would object to making all test data public, including data on nonspecification materials sold to private customers (this point was emphasized by several respondents).
4. If clear guidelines for the type and frequency of testing were supplied and if record keeping were kept simple, we would have no objection. We would object to allowing government agencies to inspect each and every test report in the producer's files.

Although some of the respondents expressed doubts that a workable system of producer control could be defined to the complete satisfaction of both buyer and seller, it is believed that such systems are evolving and that in a very few years commercial aggregate sources will be certified in much the same manner as many other manufacturing operations are. In short, effective quality control by the producer will be the basis for quality assurance by the consumer.

ROLE OF STATISTICS IN PROCESS CONTROL AND ACCEPTANCE

If possible, it would be desirable to establish guidelines that could be followed by production personnel who have had no training in statistics. With this in mind, the following practical considerations are offered.

A fully workable, statistically valid aggregate specification, from both the practical and the legal viewpoint, should describe

1. What characteristics are needed by the aggregate for particular end uses;
2. What tests will be made to evaluate these characteristics;
3. How the material will be sampled, by whom, at what stage in the production process, and how frequently;
4. The size of the lot (or sublot) to be represented by a sample or a specific number of samples (a lot, in the case of aggregate, should refer to an isolated specific quantity of specific size of a given product from a given plant produced by a given, unchanging process);
5. The extent to which a sample or samples may fall outside a target range without being rejected; and
6. The formula for determining whether a given lot is in reasonably close conformity with specified limits and acceptable at full price or at clearly defined price adjustments.

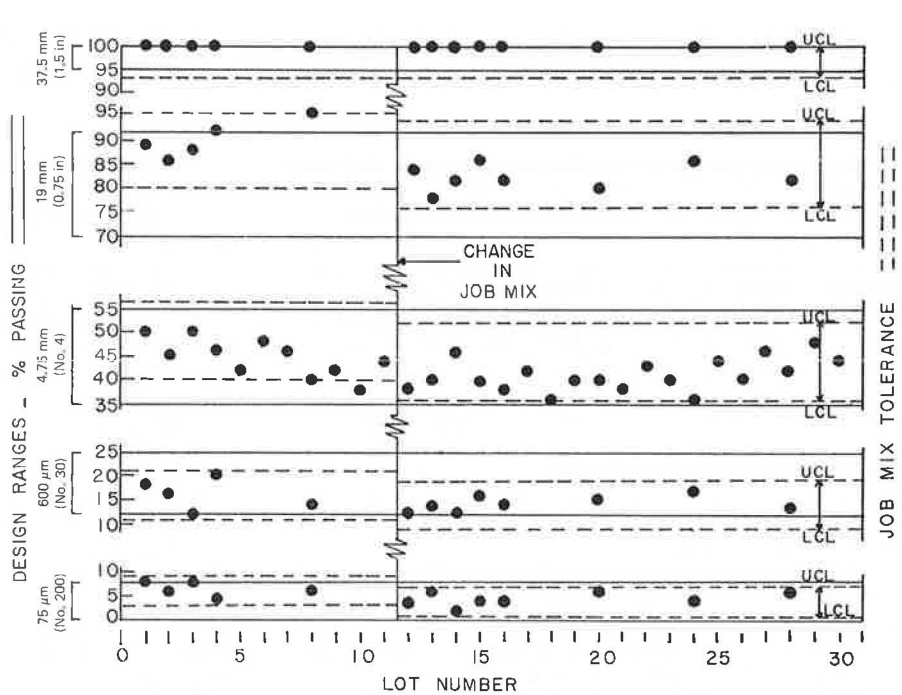
Probably the greatest obstacles to the development of fully reliable producer quality assurance systems for processed aggregates relate to the inadequacy of certain test methods and common sampling practices. As noted earlier, gradation testing lends itself best to producer control. ASTM standard method C 136 (AASHTO T 27) for sieve analysis is reasonably precise and should pose few problems when sampling is done properly. Other tests, particularly ASTM C 88 (AASHTO T 104) for soundness by use of sodium or magnesium sulfate, may be so imprecise as to be completely impossible to apply under specifications of the type considered here.

The importance of sampling cannot be overemphasized. When the producer's control records are to be the basis for acceptance, subject to occasional monitoring by the state, all samples must be taken in a statistically sound manner. ASTM standards D 75—Methods of Sampling Aggregates—and C 702—Methods for Reducing Field Samples to Testing Size—outline the principles involved. The field sample should consist of "at least three approximately equal increments, selected at random, from the unit being sampled," such as the amount in or needed to fill a haul truck, and these increments should be mixed together thoroughly and split or quartered to test portion size (obviously, the reduction to test portion size should be performed at the sampling site).

The unit to be sampled should be neither too small nor too large. A single increment of aggregate taken from a single spot on a conveyor belt, in a truckload, or from a stockpile merely accentuates unimportant within-batch variations and tells nothing about the characteristics of a unit of any significant size. But even three or more increments taken over widely separated intervals of production and mixed together may not reveal undesirable batch-to-batch variations. ASTM D 2940 gives the sound advice that acceptance decisions be based on average results from samples taken in accordance with ASTM D 75 from "at least 3 units or batches picked at random" within a lot of not more than 2700 Mg (3000 tons) of graded aggregate. A unit is defined as "the amount of material required to fill at least one normal sized haul truck."

Where the producer's records form the principal basis for acceptance, care must be taken in monitoring the accuracy of the producer's testing program. Runkle and Hughes (2) have described a statistically sound monitoring system for pug-mill-mixed aggregates. Weekly comparisons are made between the producer's

Figure 1. Control chart for aggregate base material produced to comply with ASTM D 2940.



test results and monitoring test results for all data accumulated since the job mix formula was established for a given material. Statistical tests are made to determine whether either the mean values ($\bar{x}$) or standard deviations (σ) determined from monitoring tests differ significantly from those determined from the producer's tests. Proper account is taken of the fact that far fewer monitoring test results than production test results are available on which to compute standard deviations; therefore, the standard deviations from the monitoring tests are normally higher than those from the production tests. How much higher they are determines whether there is a significant difference.

Samples for either production or monitoring tests should always be obtained by the procedure described above. To give the state a more valid statistical comparison for checking the accuracy of the producer's control program, the monitoring test portion and the production test portion should preferably be split from the same field sample.

If variability in gradation is to be held at a minimum, careful processing is essential. Consistent gradations are seldom if ever noted in unprocessed aggregates taken directly from natural deposits. Frequent gradation checks can best be and should be made by the producer so that variability can be detected and promptly corrected. FHWA's FCP Project 4F (1) includes an investigation of a number of short-cut, rapid methods of checking gradation. One of the best of these is gap sieving—checking the percentage passing only one or two key control sieves at frequent intervals and running the complete sieve analysis only on every fourth sample or so. This and a number of other short-cut procedures have been reported (3), are being evaluated, and should be carefully considered in establishing producer control systems.

RECORD KEEPING

Although most stone producers do exercise good quality control, feeling that it adds value to the final product commensurate with its cost, some producers have definite reservations about being required to maintain voluminous records in order to be certified as an acceptable source. It is recognized that variability must be minimized and that records must be complete to document compliance with specifications that penalize variability beyond reasonable limits; nonetheless, it is felt that these records need not be so complex as to be unduly burdensome.

Probably the simplest way to record the results of gradation tests and show trends in variability is by means of a control chart. Such charts may be used to record either (a) percentages passing all specified sieves for each lot tested or (b) percentages passing only one or two key sieves for each lot and percentages passing any other sieves for every fourth or fifth lot only.

Figure 1 shows one use of the control chart. The example relates to base material production for compliance with ASTM D 2940. Results for the first few lots are recorded for all sieves, after which only those for the minus 4.75-mm (no. 4) sieve are determined and recorded routinely. As a check, however, the complete gradation is recorded for every fourth lot. Note that, as a trend toward a coarser gradation was noted, a new job mix formula was submitted and approved.

Some specifications require computation of standard deviations as a measure of variability over a period of time, often for the entire quantity of a given type of material on a project. In Virginia, for example, penalties may be assessed for deviations from job mix tolerances on base materials lot by lot, and a further penalty may be assessed for excessive standard deviation over the entire project including lots already penalized.

Although standard deviations are easy to compute and are statistically "pure," it is felt that control chart records that show either average test results for individual lots or "moving averages" for the most recent four or five tests should provide an adequate picture of variability.

Whenever a change in the basic job mix formula is requested and allowed, new upper and lower control limits must be plotted on the control charts; if standard deviations must also be recorded, a separate population of test values should be established to document the degree of control obtained with respect to the new formula.

Note in Figure 1 that the "master" or design ranges under D 2940 merely define the limits of the job mix target values for the respective sieve sizes and that the full tolerances apply even though individual test results may fall beyond these limits.

The California Department of Transportation (DOT) (4) has used the moving average concept in specifying aggregate gradations for many years, applying fairly wide limits to individual tests and a narrower tolerance to the average of the most recent four or five tests. The California DOT also gives the contractor some leeway in selecting target values x for the percentage passing certain intermediate sieve sizes. Control charts can be used to record both individual test results and moving averages.

The various methods of defining a lot for acceptance purposes or establishing schedules of penalties for noncompliance are outside the scope of this paper. The Virginia system, mentioned earlier and widely publicized through FHWA pilot courses held at numerous locations since late 1976, bases acceptance on the results of four tests per lot of a designated size but, as noted, places the producer in double jeopardy by the threat of additional penalties where variability between lots is judged to be excessive. Whatever method is chosen, compliance can be judged at least as well from process control chart records as from voluminous test reports issued by state personnel.

CONCLUSIONS

1. The crushed-stone industry has practiced quality control in one form or another for years, and most producers feel it to be well worth the effort and cost. The industry generally would approve the concept of a structured quality control system, the records from which could largely replace the voluminous test reports now filed by state inspectors as the basis for acceptance.
2. Producers of stone would cooperate with user agencies by making quality control test data available for incorporation in project records; however, many would object to disclosing test data on miscellaneous sales of unspecified materials to private customers.
3. It should be expected that government agencies would wish to take occasional check samples to monitor the effectiveness of the producers' control. With this in mind, it is important that both producer and inspector use an identical, sound sampling technique—the monitored samples preferably being a portion of a regular production sample.
4. All samples in a producer control system, either regular or monitoring, should be taken from the material as produced; the effectiveness of a producer's control cannot be judged from samples taken after the material has been rehandled one or more times before it finds its way into the work.
5. Record keeping should be kept simple; control charts are preferable to stacks of individual test reports and complex forms for statistical computations.
6. Specifications should place a premium on product uniformity and permit only minimal deviations from a job mix formula but should provide considerable latitude to the producer in establishing a formula that best fits the producer's operation and requires little or no waste of fractions of usable size.

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Development of Process Control Plans for Quality Assurance Specifications

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Statistically based quality assurance specifications, such as the restricted performance bituminous specification of the Pennsylvania Department of Transportation, provide a clear delineation between the acceptance responsibilities and the process control responsibilities of the highway agency and the contractor or material supplier. They also usually require that a process control plan be submitted for approval before the commencement of work. Because the available technical literature has favored the acceptance phase, there is currently little guidance available to these parties when they prepare such a plan. The need for such guidance is illustrated by presenting the two extreme approaches that may be taken to meet the requirements of the Pennsylvania Department of Transportation. The first case illustrates the "ideal" process control plan that can be developed if a literal interpretation of the specification is made. This plan clearly requires excessive documentation. It is contrasted with the process control plans currently being submitted to the Pennsylvania Department of Transportation, which do not provide enough detail to allow a determination of adequacy. A need is thus indicated for the industry to develop technical information that provides guidance in the development of plans that are somewhere between these extremes.