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Process Control in the Construction Industry

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Contents

Controlling the Quality of Construction Aggregates Through Process Control

Reid H. Brown, Vulcan Materials Company, Birmingham, Alabama

The Georgia Department of Transportation and the Georgia Crushed Stone Association have worked together to develop a functional quality assurance system that requires the producer of construction aggregates to be responsible for process control and to certify to the state compliance with specifications. A state acceptance program maintains a check on the effectiveness of the program. A quality control program developed by the Vulcan Materials Company in support of the state program is described. This support program not only provides for proper sampling and testing but also includes a well-managed system of collecting and statistically analyzing test data through the computer, which can be used as an effective management tool. Eight computer printout reports are generated. Histograms provide valuable insight into the magnitude and causes of variations in product quality.

Historically, most contracting agencies have had specifications that provide for inspection and testing to be administered directly by the agency itself for controlling the quality of construction aggregates. Generally, these specifications have been punitive; thus, inspection and testing have become policing functions rather than a management tool to effect product quality. These types of specifications fail to provide the necessary incentives to aggregate suppliers to motivate them to accept their responsibility to effect aggregate quality through process control.

Although construction aggregates are a manufactured product and usually represent the greatest quantity of any material used on a project, they are uniquely different from other materials. Because of economic considerations, aggregates must be provided from local resources. Thus, once an aggregate resource has been selected through proper geological and engineering evaluations, the inherent physical properties (specific gravity, abrasion loss, sulfate loss, and so on) and chemical properties of the aggregates produced are essentially fixed. There are a few deposits in which selective mining and special processing procedures are required to improve the properties and upgrade the quality of the aggregate. These special considerations are not considered in this paper; rather, it is limited primarily to control of aggregate gradations and cleanliness. Fortunately, many of the concepts that apply to gradation control are also applicable to the control of other properties.

During the past few years, the construction industry, particularly the highway segment, has recognized the merits of the "end-result" specification concept, according to which the responsibility for quality control lies with the contractor and material suppliers. Through quality assurance concepts, criteria and methods are established by contracting agencies to assure them that the products they receive are produced under properly controlled conditions and in compliance with specifications. For a contractor to successfully operate under an end-result specification, he or she must be furnished from a reliable source with materials of the right quality. Thus, the concept of process control becomes very workable and necessary to an aggregate producer's operation when material is produced for a project under end-result specifications.

The Georgia Department of Transportation and the Georgia Crushed Stone Association have worked closely together to develop a functional quality assurance system for furnishing aggregates for use in state work. The system requires the producer to be responsible for process control and to certify to the state compliance with specifications. The state has established a quality acceptance program to maintain a check on the effectiveness of the producer's program.

Vulcan Materials Company, a major producer of construction aggregates, has developed a quality control program in support of the state program. The purpose of this paper is to describe this support program and some of the benefits that have resulted since it has been implemented.

BACKGROUND

The aggregate industry has traditionally been an unsophisticated business. The nature of the business, in general, is local because of the high transportation costs associated with the movement of materials and the low unit value of aggregate. Most of the existing aggregate processing plants have grown from small, family-owned businesses that were generally concerned with "how to get it out of the ground." The responsibility for sampling, testing, and accepting material was left to the customer—the highway department. Frequently, the highway department was required to resort to rather thorough inspection and testing programs to ensure acceptable quality and compliance with specifications. As a result, they found themselves in the position of running the aggregate business for the producer. This, of course, was undesirable and awkward for all concerned. Testing and inspection were costly to the state and, under such conditions, not too effective. For example, during the early 1970s, the state of Georgia had over 400 personnel assigned to aggregate testing.

Several years ago the aggregate industry was challenged to develop and implement an effective quality control program to effect better process control. It has taken considerable effort and encouragement by a few of the more progressive highway departments and the Federal Highway Administration to interest the industry in the concept.

QUALITY ASSURANCE BY THE STATE

The Georgia quality assurance program was developed through a cooperative effort between the Georgia Department of Transportation (DOT) and the Georgia Crushed Stone Association and was implemented in February 1975. The program is strictly voluntary, and participation by the producer is optional. Since its beginning, all producers of coarse aggregate have elected to participate. Since sand plants are generally much smaller and mostly operated by local contractors, only about 25 percent have elected to participate. If producers elect not to participate in the program, their material is sampled and tested by the state at the plant and project sites as it was before. To qualify for participation in the program, the source of material and the quality control program must meet the following criteria:

1. A mutually agreeable quality control program, between the DOT and the producer, must be established for each plant based on the characteristics of that plant

and its deposits as well as past performance.

2. Each plant must have an approved laboratory. Laboratory equipment and facilities must be certified.

3. Sampling and testing personnel must be trained and certified.

4. To ensure uniformity of testing between the DOT and the producer, one sample per quarter is tested at the producer's laboratory and then shipped to the state's laboratory for comparison testing.

5. Correct load-out of materials, including cleanliness of all haul units and accurate identification of products, are recognized as producer responsibilities and are considered an integral part of the quality control program.

6. Delivery of aggregate from a source that has an approved quality control program is certified by the producer to comply with the specification and need not be tested at the project or at the plant before use unless nonuniform or nonspecification material is suspected by the DOT.

7. To substantiate the quality of the material actually incorporated in the work and to evaluate the quality assurance program, certain evaluation procedures are followed. The DOT samples and tests on a regular but random basis at the source of production and on occasion at the project site. Sampling and testing are done as often as required to evaluate the effectiveness of the producer's quality control program.

8. The producer is required to sample and test at an agreed frequency for each type of material being furnished to the DOT. Producer certification is made on an approved DOT form. The producer's records are sent to the DOT for their records. Each load of material need not be tested, but the shipments represented by a particular sample should be indicated on the reports by a project number and other necessary identification.

9. The producer is responsible for keeping separate, if necessary, the different materials used for different purposes by the DOT, such as material for asphalt concrete, portland cement concrete, graded aggregate base, and other mixtures.

10. Regular samples are taken at the project at frequencies prescribed by the DOT.

11. Certification of facilities and personnel is the responsibility of the DOT. Certification is made at the request of the producer. Subsequent recertification is required annually or based on personnel changes or problems detected in the system.

This is a summary of what is required by the Georgia DOT for a producer to participate in a product certification program. This system thus far has been most effective. As previously mentioned, before implementation the DOT had approximately 400 people sampling, testing, and inspecting aggregates in the state of Georgia; now there are 12. In addition, before implementation the state experienced frequent problems with material that did not meet specifications; since implementation, the number of problems has been reduced significantly.

PROCESS CONTROL BY THE PRODUCER

Initially, the producers were somewhat reluctant to participate in the program because they felt they were being required to add personnel to their staff to inspect and maintain a quality control program for the state, thus adding to their operating costs. Experience has shown that it takes about 1 person/909 000 Mg (1 person/1 000 000 tons) of capacity to properly maintain a quality control program. Depending on the size of an operation, the cost to a producer will be between \$0.01 and \$0.02/Mg (ton). This is a significant cost and a very tangible one, and any good business would require a justification before such an expenditure was approved. Unfortunately, the benefits of a producer quality control program are not readily apparent, and some are intangible in nature, much like technical services or research and development activities.

However, soon after the Georgia program had been implemented, the industry recognized that the program offered many advantages that certainly overshadowed the costs of the program. The most significant contribution was that the responsibility of producing quality, and therefore the mechanisms to effect quality, were given to the producer. Flexibility of plant operation, less rejected material, technical services, and goodwill are but a few of the advantages that have emerged from this program. Obviously, the quality of the material has to be controlled at the plant, and the producer is in the best position to perform this function.

VULCAN QUALITY CONTROL PROGRAM

During the early 1960s, when Vulcan was emerging as a leader in the aggregate industry, its management recognized that a research and development capability merited attention. Thus, they formed one of the first research and development groups in the industry. A part of the defined function of the newly formed research and development section was quality control, but it was not until 1972 that this program became fully functional. The program has assisted measurably in improving the quality of material being produced in those divisions that are using it. The development of Vulcan's quality control program has been closely related to and associated with the evolution of the certification and end-result specification program of the Georgia DOT.

Vulcan's program has had the support and encouragement of its top management, which is an essential aspect of the success of a quality control program. The following items have been identified as contributing to a good, functional quality control system:

1. Qualified personnel;
2. A well-planned, written system approved by management;
3. Good housekeeping and preventive maintenance practices;
4. Correct sampling and testing procedures;
5. Proper data analysis; and
6. Use of the results in engineering and management decisions.

Vulcan has now implemented its quality control program in about one-third of its plants. It is functioning in those states in which highway departments encourage producers to maintain their own quality control programs. In three of these states, the highway departments now accept product certification from the producer in lieu of state testing.

At each of the participating plants, an adequately equipped laboratory is maintained and manned by a trained quality control technician. This technician is under the supervision of the quality control manager, who, in turn, reports to division management. All quality control activities are overseen and monitored by the corporate quality control manager, who is a professional engineer.

More than a policing activity was desired. One of the basic premises of the program was that information developed from testing, if obtained and analyzed correctly, could be a valuable asset to management.

To assist in the management of Vulcan's quality control program, a computerized statistical quality control system was developed. The system consists essentially of input data collected from the sampling and testing activities of the plants. The information is routed to the computer on a routine basis, and at defined points in time the data are statistically analyzed and reduced to a usable format. Currently, access to eight different reports is available each month. A brief description of each report follows.

Exception Report

The exception report is prepared as a tool to enable management to make a quick assessment of any significant problems. It lists all tested samples of a product that are outside specification limits and provides, through statistical concepts, information on potential problems that may require corrective attention.

Frequency of Sampling Report

The sampling report provides information on the total number of samples tested at a plant by day and by month for each product.

Time-Sequenced Values Report

The values report is basic. It shows all the samples tested at a plant as well as the date, time of day, and gradation for each product.

Product Uniformity Report

The report on product uniformity provides information for comparing the quality of a particular product from one plant to another. It may be used to compare the uniformity of the mean percentage passing and standard deviation for a given product between plants and to compare the monthly performance of a plant with year-to-date performance.

Control Chart Limits Report

The control chart limits report provides data for the purpose of preparing quality control charts that are used by the inspector and superintendent at the plant to control quality during production.

Average Gradation Analysis and Standard Deviation Report

The report on average gradation analysis and standard deviation provides for sales personnel and customers a listing of mean percentage passing and standard deviation for all products produced at a plant.

Yearly Statistical Comparison Report

The yearly statistical comparison report lists the average gradations and standard deviations by month for all products sampled during the previous 12 months. Seasonal patterns and fluctuations can thus be identified and anticipated.

Histograms

For each sampled product for which sufficient data are available, a histogram is plotted for each sieve size tested. If samples are properly selected and tested, a "bell-shaped" curve is generated. If the plots do not approach such a shape, it is an indication that some procedure may be incorrect and corrective action may be required.

Information obtained from these reports is providing valuable insight into the type and cause of variation that occurs in the various products. For example, it has been found, as would be expected, that the point of sampling makes a considerable difference in the magnitude of the variation. If an ASTM No. 57 aggregate (typical concrete-sized coarse aggregate) is sampled from the production belt just before it is discharged into stock or a loading bin, the variation on the 13-cm (0.5-in) control screen may be as low as 2 to 4 percent. If this same material is sampled under controlled conditions from a railcar or a truck, the variation will be in the range of 4 to 6 percent. If it is sampled from a stockpile, it can be as high as 10 percent. We believe that this type of information is extremely valuable in establishing specification limits, methods of sampling, and tolerances in specifications and in assisting in the mix design for portland cement concrete, asphaltic concrete, and crushed-stone base.

SUMMARY

Vulcan's statistical quality control system has been a very effective aid in controlling quality and in knowing what is being produced. It is a valuable management tool. Among the advantages the program provides are the following:

1. It documents in a concise and orderly manner the quality of all products;
2. It satisfies the record-keeping requirements of state highway departments that are using or considering product certification programs in lieu of their present inspection procedures;
3. It optimizes the amount and timing of sampling;
4. It provides effective information to sales personnel and services to customers;
5. It reduces the amount of material shipped that does not meet specifications;
6. It provides a valuable library of information that may be adapted to research and development programs;
7. It provides an effective tool for operating, maintaining, and upgrading plant control;
8. It makes it possible to identify and anticipate seasonal fluctuations;
9. It maximizes product quality commensurate with operations, sales, and marketing conditions; and
10. It provides a more competitive atmosphere in the construction materials industry.

Vulcan's system has been designed to provide dependability and accuracy. It ensures a high probability of valid data and is flexible and adaptable to all aggregate plants operated within the company. Simplicity and clarity have been prime considerations throughout the development of the quality control system.

Even though significant progress has been made by a few states in the implementation of producer quality control systems and product certification, several factors are still deterring the concept from being widely accepted by highway departments and producers. Many producers see the program as costing them money and feel that there are no ways for them to recover incurred costs. Quality control is one of those functions that are somewhat intangible: The cost and effort of the activity are easily identifiable but the benefits are not. These obstacles can be overcome only by educating the producers and through experience.

It is important that the program be simple to administer and require a minimum of paperwork. An effective program need not be complicated and bureaucratically burdensome. A producer is much more receptive and 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

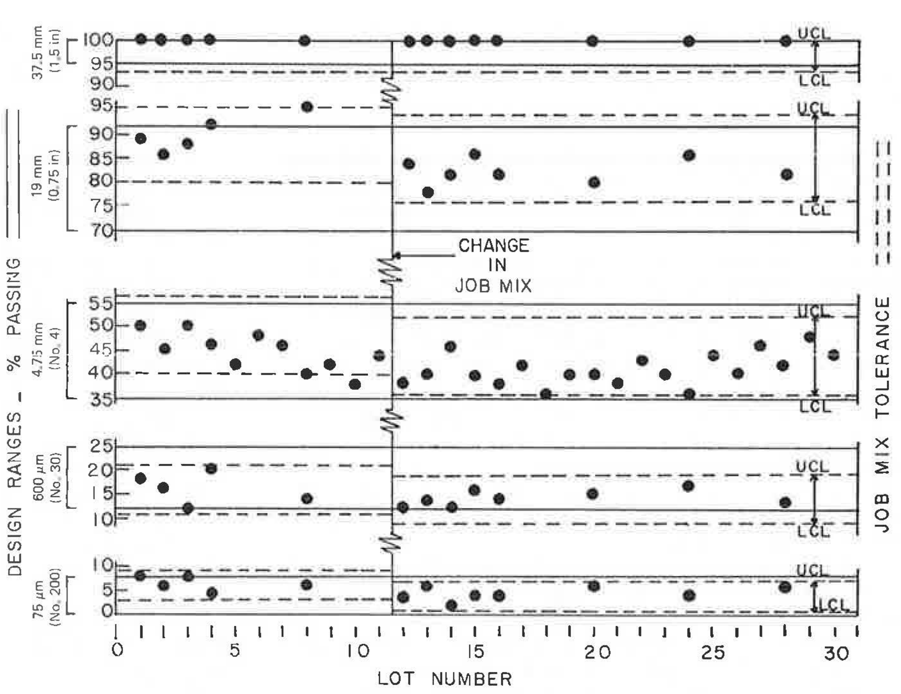

Figure 1. Control chart for aggregate base material produced to comply with ASTM D 2940.

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.

The final quality of a highway is to a large degree a function of the care and concern that is exercised by the material suppliers and the contractors who provide and place the materials used in its construction. If haphazard and inefficient control is exercised, these parties will suffer economically because of either excessive rejection rates or process overreaction (i.e., the use of more cement than is required to avoid rejection of the material).

Interest in process quality control has grown as more state highway agencies have adopted statistically based quality assurance specifications that require contractors and material suppliers to submit process control plans to qualify for consideration on projects. The objective of this paper is to indicate that the highway construction industry, through its trade and contractor associations, must take the lead in providing guidance and technical advice to its members with regard to the development of such plans.

First, a brief background of statistically based quality assurance specifications is provided, and then some of the aspects of the restricted performance specification for bituminous concrete implemented by the Pennsylvania Department of Transportation (PennDOT) (1) are examined. An "idealized" approach to the development of a process control plan that interprets the statements in that specification in a literal fashion is then presented. This is followed by the presentation of some examples of actual process control plans that have been submitted in response to that specification. These two extremes indicate that the development of practical, well-defined plans that provide the maximum benefit to material suppliers and contractors in terms of efficient control of their processes is still experiencing growing pains.

BACKGROUND OF QUALITY ASSURANCE SPECIFICATION

Quality assurance, broadly interpreted, refers to the total system of activities that is designed to ensure that the quality of the construction material is acceptable with respect to the specifications under which it was produced. It addresses the overall problem of obtaining the quality level of a service, product, or facility in the most efficient, economical, and satisfactory manner possible. The scope of the total quality assurance system (regardless of the type of material specification used) encompasses portions of the activities of planning, design, development of plans and specifications, advertising, awarding of contracts, construction, and maintenance.

Types of Specifications

At the heart of such a quality assurance system are practical and realistic specifications for construction materials. A practical specification is one that is designed to ensure the highest achievable quality of the resulting construction. A realistic specification is one that recognizes the fact that (a) there is a cost associated with every specification limit and (b) the characteristics of all products, processes, and construction are by their very nature variable.

In highway construction, the three most common types of specifications are (a) end result, (b) material and methods, and (c) statistically based quality assurance.

End Result

A pure end-result specification places the entire responsibility for supplying an item of construction or material of specified quality on the contractor or producer (2, p. 35). This type of specification places no restrictions on the materials to be used or the methods of incorporating them into the completed product. The responsibility of a highway agency is therefore reduced to either accepting or rejecting the final product or applying a penalty system that accounts for the degree of noncompliance.

Material and Methods

Most highway agencies have traditionally used the material and methods type of specification. It is more frequently referred to as the reasonable conformity or substantial compliance type of specification. In this type of specification, the contractor or producer is directed to combine specific materials in definite proportions, use specific types of equipment, and place the material or product in a prescribed way. Each step is controlled and in many cases directed by a representative of the highway agency. By specifying the procedure, the highway agency has obligated itself to a great degree to accept the end product even though there is no assurance that it will meet the performance requirements. The statement that the contractor is responsible for the end result under this type of specification is of questionable legality if the contractor has met the materials and methods requirements.

Statistically Based Quality Assurance

As noted by Bolling (3, p. 17.13) and the National Cooperative Highway Research Program (2, p. 38), a number of state highway agencies have already partially adopted statistically based specifications in some of their material specifications.

Generally speaking, the quality assurance specification bridges the gap between the two types of specifications mentioned above. In basic intent, it is performance oriented. The distinguishing elements of a quality assurance specification are

1. Performance-oriented acceptance criteria;
2. Use of statistical techniques for the purpose of (a) ensuring unbiased quality information, (b) effective and timely process control, (c) objective evaluation of quality characteristics in terms of both central tendency and dispersion, and (d) making acceptance decisions on a rational basis; and
3. Clear delineation of responsibilities with respect to (a) process control by the contractor and (b) acceptance sampling, testing, and inspection by the owner (the state highway agency).

Reference to the two elements in item 3 is made in the form of a process control plan and an acceptance plan.

Construction Subsystem in Quality Assurance Specifications

An analysis of the construction subsystem within a statistically based quality assurance system will indicate how this type of specification differs from end-result and materials and methods specifications. There are two independent parties involved in the subsystem: the highway agency and the contractor. It is a fundamental requirement that the responsibility for quality be assigned commensurably according to the role each party performs in the construction subsystem. The contractor (or material supplier) has the most direct and profound effect on the quality of the work and should therefore be responsible for exercising process control. The highway agency acts as the legal agent of the buyer—the taxpayer—and is therefore intensely interested in the final quality of the product it buys. The highway agency therefore performs the acceptance sampling, testing, and inspection to make sure it is receiving the specified level of product quality.

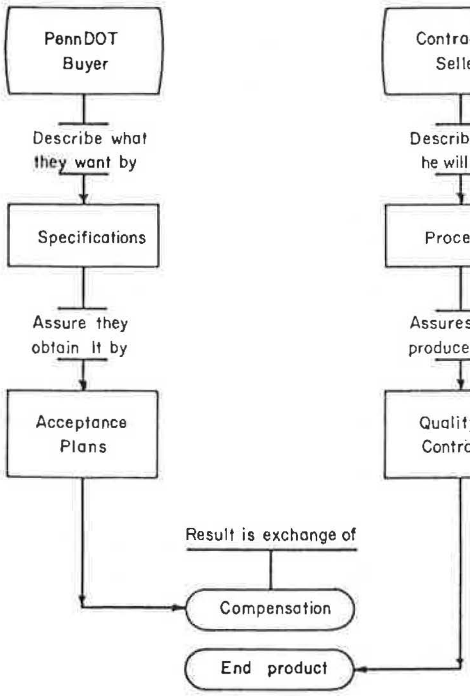


Figure 1. Two-party relation of quality control and acceptance plans.

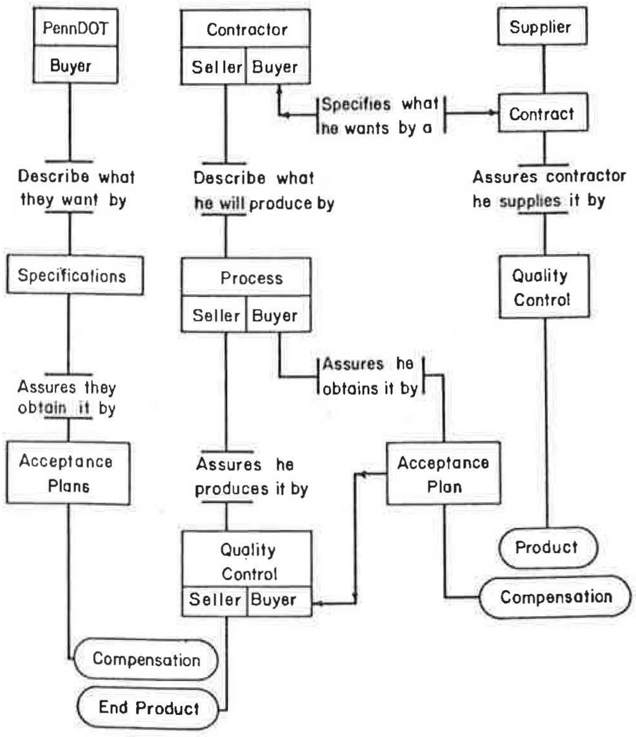


Figure 2. Three-party relation of quality control and acceptance plans.

Statistically based quality assurance specifications provide a clear division of responsibility for these two roles. In fact, for this type of specification, it might be stated that quality assurance (QA) is equal to process control (PC) plus acceptance sampling, testing, and inspection (AST&I) [i.e., QA = PC + AST&I (4, p. 2)]. In this equation, PC represents all those activities that are primarily carried out by the contractor or producer of a given product for the purpose of maintaining product quality at some specified standard. AST&I represents all those activities associated with the owner's (state highway agency's) efforts to determine that they received that for which they contracted.

It should be noted that the material supplier also occupies an extremely important position with regard to process control since in most instances the material supplier initiates process control activity.

RESTRICTED PERFORMANCE SPECIFICATION FOR BITUMINOUS CONCRETE

PennDOT currently has a restricted performance specification for bituminous concrete that is incorporated as a special provision on bituminous concrete contract projects that meet the following criteria:

1. The estimated quantities for each course of mainline paving must be a minimum of 2721 Mg (3000 tons).
2. The thickness of the surface course must be 3.81 cm (1.5 in) or greater.
3. Paving must be carried out on a properly prepared, stable base.

Figure 1 shows the relation that is envisioned when only PennDOT and a contractor are involved, and Figure 2 shows the relation when a material supplier is added to the picture. It should be noted that quality assurance specifications normally require fewer material characteristics to be tested for acceptance purposes than for process control purposes. This fact is illustrated below for the PennDOT specification.

Acceptance Testing

The PennDOT specification states that acceptance tests for bituminous concrete be performed at the mixing plant for percentage of bituminous content and at the completed pavement for compaction (ultimately, thickness and smoothness will also be incorporated in the acceptance criteria).

At the batch plant, acceptance is made on a lot-by-lot basis. The specification (1, p. 1.4) states:

> A lot shall consist of a minimum of 2721 metric tons (3000 tons) and shall be divided into 5 approximately equal sublots. Acceptance of the mixture by extraction shall be on the basis of bitumen results of five consecutive random samples for each lot. One random sample shall be taken from each sublot. Acceptance of the mixture by printed tickets from automated and recordated plants shall be based on the bitumen results of five consecutive random printed tickets for each lot. One random printed ticket shall be taken from each sublot.

The percentage bitumen content of the lot is expected to meet the approved job mix formula within the tolerances shown in the specification for either extraction tests or the printed tickets from automated recordated plants. A determination of the acceptability and the level of payment (i.e., whether a full or adjusted price is paid) of the lot of material in terms of bitumen content is made by calculating the estimated percentage of material within the allowable specification limits (1; 5, Session 20; 6; 7; 8).

Acceptance of the completed pavement is also made on a lot-by-lot basis. As noted in the specification (1, p. 1.9),

> A lot shall consist of not more than 1524 m. (5000 linear feet) of paving lane or 5601 sq. m. (6700 sq. yds.), whichever is lesser, of each layer or course but shall not exceed one day's construction. A lot will be subdivided into 5 approximately equal sublots. Readings for each nuclear density test will be taken at a random location (selected as prescribed in PTM No. 1) on each of the 5 sublots, except that no readings shall be taken within two feet from the edge of the pavement....

The in-place density of the compacted mixture (wearing or binder course) shall be equal to or greater than 98 percent of a control-strip density that has been previously determined. If the results of the density tests on a lot indicate that less than 85 percent of the material has been compacted to the specified density, the lot will be paid at an adjusted price (4; 5, Session 20; 6; 7; 8). For payment purposes, the plant lot [2721 Mg (3000 tons)], defined for acceptance of paving mixtures at the mixing plant, and the project lot [1524 m (5000 linear ft) or 5601 m^2 (6700 yd^2), whichever is less], defined for acceptance of completed pavement in place, are independent of one another. Nonconforming lots are paid for at an adjusted contract unit price by considering bitumen and density individually.

Process Control Testing

In a pure end-result specification, the contractor and material supplier would be left to their own devices with regard to the number of other bituminous concrete characteristics that they felt should be controlled. This situation does not exist with the PennDOT specification, however, because both a set of required process control activities and a set of additional recommended process control activities are incorporated in the specification.

The required activities can be described as follows:

1. Control of aggregates—After the job mix formula is approved, the contractor must control the aggregates so that the hot-bin gradations meet the approved job mix formula within the tolerances shown in the specifications as determined by the contractor's quality control tests. A minimum of one hot-bin gradation analysis shall be made from each sublot.
2. Control of the completed mixture—The specification indicates that the completed bituminous mixture shall be sampled at random intervals at the plant as directed by the engineer. At least one Marshall test shall be made from each sublot. Each Marshall test shall consist of the average of three test portions prepared from the same sample increment. Testing shall be done in accordance with Pennsylvania Test Method (PTM) 705. If the results of any three consecutive Marshall tests of any property do not conform to the requirements in the specification, the contractor shall take immediate corrective action.
3. Control of completed mix temperatures—The specification indicates that the temperature of the aggregate shall be so controlled that the temperature of the completed mixture taken at the plant shall be as specified within the tolerances shown in the specification. The temperature of the completed mixture shall be determined by inserting a quick-reading dial thermometer at different locations in the truckload of bituminous mixture. A minimum of two temperature measurements shall be taken.

In addition to the above required process control activities, it was noted earlier that a set of suggested process control activities is incorporated in the specification. The most important aspects of these suggested guidelines are outlined below (units of measurement are given in U.S. customary units):

A. All types of plants
  1. Cold bins
    a. Determine aggregate gradation of each bin
    b. Determine gate settings of each bin to ensure compliance with job mix formula
  2. Hot bins
    a. Determine aggregate gradation of each bin
    b. Determine overrun in coarse aggregate bins
    c. Determine theoretical combined grading
  3. Bituminous mixture
    a. Ross count
    b. Aggregate gradation
    c. Percentage of bitumen
    d. Mixing temperature
B. Weight batch increment type plant
  1. Batch weights
    a. Determine percentage used and weight (lb) of each bin to ensure compliance with job mix formula
C. Continuous volumetric proportioning plant
  1. Hot bins
    a. Determine gate calibration chart for each bin
    b. Determine gate settings of each bin to ensure compliance with job mix formula
  2. Bituminous material
    a. Determine gallons per revolution or gallons per minute to ensure compliance with job-mix formula
D. Weight scales and asphalt pumps
  1. Calibrate scales and pumps
  2. Check calibration of scales and pumps

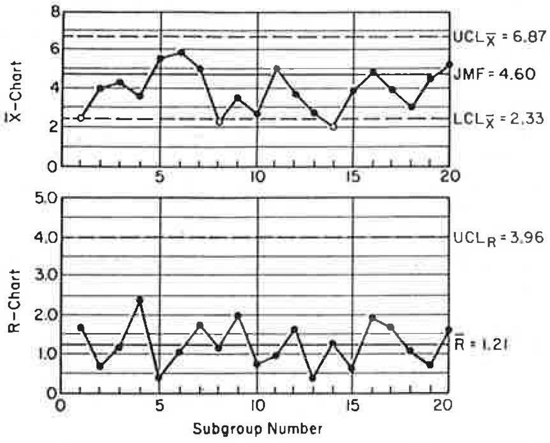
Dilemma of Contractor and Material Supplier

The above presentation and the outline given indicate the dilemma that faces the contractor or material supplier. From the bituminous supplier's viewpoint, for instance, a process control plan must be developed that incorporates the following testing elements:

A. Acceptance testing—percentage bitumen content, 2721-Mg (3000-ton) lot, five sublots
B. Process control testing (required)
  1. Hot-bin gradations—a minimum of one gradation analysis per sublot
  2. Marshall test—a minimum of one test per sublot
  3. Completed mix temperature—a minimum of two temperature tests per truckload
C. Process control testing (suggested)
  1. Cold-bin gradations—no minimum testing requirements
  2. Hot-bin gradations—no minimum testing requirements stated
  3. Bituminous mixture (Ross count, aggregate gradation, percentage bitumen, mixing temperature)—no minimum testing requirements stated

The plant technician must be provided with a random sampling schedule that allows all of these tests to be taken in an efficient manner. This schedule must reflect a decision about how the acceptance sampling requirements are overlayed onto the process control

Figure 3. $\bar{X}$ and R combined hot-bin gradation control charts [percentage passing 0.074-mm (no. 200) sieve].



activities. A decision must be made about whether the size of sublots, the number of tests in a sublot, and so on will conform to PennDOT acceptance sublots, for example, or whether acceptance testing and process control testing should be designed as independent systems. The method of documenting the test information must also be determined.

Very little information is currently available to the individual material supplier who is seeking guidance in making these types of decisions. The complexity that is involved will become more evident as proposed plans that represent reactions to the requirements are presented in the remainder of this paper.

PROCESS CONTROL TECHNIQUES

The underlying intent of process control from the viewpoint of a contractor or material supplier is to ensure that the material is accepted without penalties. The contractor or supplier should be able to tell before the acceptance phase whether the proper level of quality is being furnished by establishing and maintaining a practical process control system that has been designed based on his or her own needs.

Some material characteristics can be adequately controlled by merely providing a tabulation of results. A given process, however, is typically considered to be "in control" if both the central tendency and the dispersion (i.e., variability) of the process are controlled. The sources of variability that influence a process are

1. A system of chance causes that, because they are inherent in the process, cannot be eliminated and
2. A system of assignable causes that represent errors and mistakes that must be recognized and removed if a process is to stay in control.

The technique that allows the central tendency and the dispersion of a particular material characteristic to be "charted" as the material is being produced and at the same time identifies when either chance causes or assignable causes are acting on the process is called a statistical control chart.

Statistical Control Chart

Background

According to Duncan (9, p. 316),

> A control chart is a device for describing in concrete terms what a state of statistical control is; second, a device for attaining control; and, third, a device for judging whether control has been attained.

This is accomplished by establishing $\bar{X}$ as well as R control charts, as shown in Figure 3. Each chart has three horizontal lines. The central line corresponds to the average or target value of the measurable characteristic (i.e., the job mix formula for the $\bar{X}$ chart and the average range for the R chart). The extreme lines represent the upper and lower control limits (UCL and LCL); the LCL for the R chart is 0. These limits are established so that values that fall between them are assumed to be attributable to a system of chance causes.

To plot the control chart, samples of size n are randomly selected from the process. It is important to note that all concepts that underlie statistical control charts are based on random sampling. The more preferred control charts from a statistical viewpoint (i.e., so that a normal distribution assumption is valid) are those with subgroup sizes of $n > 1$. This also allows both the $\bar{X}$ and the range for each subgroup to be plotted. It has been found, however, that because of economics there is a great reluctance on the part of contractors and material suppliers to use subgroup sizes $n > 1$. Whereas from the statistical standpoint the ideal subgroup size in an industrial situation may be 4 or 8 or 16, such sample sizes probably would not be practical in a highway situation. Therefore, it may be necessary to use smaller subgroup sizes, possibly even $n = 1$, and fewer total number of observations (N) in estimating the values of $\bar{X}'$ and σ' in highway construction applications.

When plotted points fall outside the control limits, a problem that may necessitate a change in the process is indicated. When a trend of points inside the control limits is identified, an adjustment in the process may also be necessary. The closer the plotted values are to the central line, the better is the control of the product.

Types

There are two general types of statistical control charts. The first is a control chart for attributes. Attributes are usually visually inspected properties such as cracks, scratches, missing parts, or materials inspected by "go or no go" gauges. No actual measurements are recorded. The characteristic under inspection is merely classified qualitatively as conforming or not conforming to a specified requirement.

The second type of control chart is the control chart for variables. A variable control chart records the actual measured quality (or the average subgroup quality) of the characteristic. Although more effort is usually required in taking and retaining a measurement, the greater information supplied by variable sampling enables a desired level of sensitivity to be obtained with fewer samples than the attribute approach requires.

Types of Variable Control Charts

The Manual on Quality Control of Materials of the American Society for Testing and Materials (ASTM) (11) indicates that many different types of variable control charts have been developed for the industrial setting. The most readily adaptable control chart techniques for use in highway construction are, however, probably limited to the following types:

1. Control chart for individual observations—Possibly the simplest control chart is that in which individual observations (i.e., $n = 1$) are plotted one by one

(11). This type of control chart is often used when sampling and testing are expensive, time-consuming, or destructive in nature.

2. Control chart for moving range between individual observations—This type of chart is often used in conjunction with the first type of chart to obtain some measure of variability.

3. Trend indicator chart—This control chart is also often used in conjunction with a control chart for individuals. Sometimes called a control chart for moving averages (12), this type of chart smooths out the normally expected point-to-point fluctuations of individual test results. It achieves this effect by plotting the moving average of several test results.

4. Shewhart control charts—This technique was originally developed by Shewhart of Bell Telephone Laboratories in the early 1930s (12) and has proved to be very effective in identifying the presence of assignable causes. It requires grouping test results into subgroups of size $n > 1$. All interpretations are based on the normal distribution. The Shewhart technique requires using two control charts. The first is the control chart for averages ($\overline{X}$ chart), which controls the central tendency of the process by examining the change in process average between subgroups. The second type of chart is the control chart for ranges (R chart), which controls the dispersion of the process by examining the variability within the subgroups. Either a control chart for ranges (R chart) or a control chart for standard deviation (σ chart) could be used for this purpose. The range chart is recommended because it is probably more easily understood by field personnel.

Presentations of the development of the equations for these types of control charts are given in the ASTM publication (11), by Willenbrock (5), and in most standard textbooks on statistical quality control.

Establishing Control Limits

The key element in the use of statistical control charts is the proper designation of the control limits for a given process. To establish control limits, the population mean $\overline{X}'$ and standard deviation σ' are needed. There are two ways in which these parameters may be obtained: (a) $\overline{X}'$ and σ' are known (for a well-defined process), and (b) $\overline{X}'$ and σ' are estimated (this requires a preliminary data collection phase).

In either case, however, it should be noted that the process data should be used to describe the process in terms of $\overline{X}'$ and σ' as well as the UCL and LCL if true process control is to be achieved. It is these values, and not those imposed by the tolerances in a specification, that determine whether a process is truly in control. A control charting technique that uses specification tolerances as the UCL and LCL will not be able to identify when assignable causes are acting on the process. It should be noted that, if a material producer keeps the process in control with respect to the UCL and LCL and these limits are tighter than the specification tolerances, the producer will never be in a penalty situation even if the process is slightly out of control. A producer may even want to relax process control activities a little in such a case.

IDEAL PROCESS CONTROL PLAN FOR PennDOT SPECIFICATIONS

A pilot research project was undertaken at Pennsylvania State University in 1975 to provide a set of process control guidelines for bituminous plants in Pennsylvania that would be operating under the new PennDOT specification (10). The report attempted to look at the specification through the eyes of a material supplier who was seriously trying to develop a process control plan that would be of value to his or her operation and would also satisfy PennDOT requirements.

The study was restricted to the production of ID-2A wearing mix at a manually operated bituminous batch plant located in central Pennsylvania (hereafter called plant A). The plant had the following characteristics: (a) 1.8-Mg (2-ton) capacity and capability of producing 907 Mg (1000 tons) of base, binder, or wearing course per day; (b) 45.35-Mg (50-ton) capacity cold bins (2B, 1B, and fine aggregates); (c) 16.33-Mg (18-ton) capacity hot bins (manual proportioning); (d) adequate testing equipment and one laboratory technician; and (e) Marshall mix design procedure. The control tests typically performed under the traditional bituminous inspections included (a) cold-feed gradation analysis (minimum of once per day per each type of mix), (b) hot-bin gradation analysis (minimum of once per day per each type of mix), (c) temperature tests (use of temperature gauges throughout process), (d) extraction test of completed mixture to determine bitumen content and gradation (minimum of once per day per each type of mix), and (e) Marshall test (minimum of once per day per each type of mix).

Recommended Procedure

The PennDOT report (10) identified the following steps that a bituminous material supplier should follow to develop a workable process control plan:

1. Assign responsibility for process control,
2. Review the quality assurance specifications,
3. Develop a sampling and testing plan,
4. Select documentation techniques,
5. Devise a format for recording data,
6. Select and establish control limits,
7. Select interpretation criteria,
8. Investigate and eliminate assignable causes, and
9. Evaluate the system.

A brief outline of steps 2 through 4 will demonstrate what a contractor's interpretation of the specification might indicate with regard to process control [an explanation of the remaining steps can be found in the PennDOT specification (10)].

Step 2—Review of Quality Assurance Specifications

A review of the specifications might indicate that the characteristics given below must be controlled for the ID-2A wearing course process:

Process Control Activity	Number of Characteristics
Hot-bin gradation	
Combined bins	8
Individual bins	
Fine aggregate	7
Coarse aggregate	3
Cold-feed gradation	
Fine aggregate	7
Coarse aggregate	3
Extraction analysis	
Asphalt content	1
Gradation	8
Completed mix temperature	1
Marshall criteria	
Stability	1
Flow	1

Process Control Activity	Number of Characteristics
Voids	1
Voids filled with asphalt	1
Total	42

It should be noted that the number of characteristics that must be controlled depends on the particular circumstances at the plant being studied.

Step 3—Development of Sampling and Testing Plan

Once the characteristics to be controlled have been identified, the next step includes a decision about the sampling and testing plan that will be used. The contractor must make basic decisions related to

1. Criteria for the frequency of sampling and testing, including (a) available manpower and testing equipment, (b) type of material, and (c) randomizing on the basis of megagrams or time; and
2. Criteria for subgroup size and designation, including (a) the method of subgrouping (n samples at one point in time or over a period of time) and (b) cost and time for performing the test (for long test procedures, n = 1, and for short test procedures, n = 2, 3, and so on).

The schedule given in Table 1 was developed for plant A when these factors were considered.

A basic assumption related to process control is that all sampling should be done on a random basis. Supervisory personnel must therefore become involved in preselecting the random times at which samples will be taken by using an appropriate random number table or other device.

Step 4—Selection of Documentation Techniques

The schedule in Table 1 does not appear to be very different from current practices at plant A since it requires roughly four hot-bin gradation tests, four cold-feed gradation tests, two Marshall tests, and two extraction tests per day in addition to a number of temperature tests. The problem appears to lie in the necessary documentation that is required so that the data can be effectively used for process control purposes.

The most informative process control system would require the use of statistical control charts for every one of the material characteristics given previously. Clearly, this system would provide the maximum assurance of high-quality material. It is recognized, however, that it would involve burdensome paperwork for the technician. For this reason, the partial use of tabulation techniques for monitoring less important control characteristics was suggested. The following plan resulted.

Control charts would be used for the most important process control characteristics, including

1. Extraction tests (for bitumen content and selected sieve sizes),
2. Hot-bin gradation tests (for selected sieve sizes),
3. Cold-feed gradation tests (for selected sieve sizes), and
4. Temperature tests of the completed mix.

The control charts used would be $\overline{\overline{X}}$ and R charts when n > 1, X and moving range charts and trend indicator charts when n = 1. Tabulation techniques would be used for the less important process control characteristics, including

1. Hot-bin gradation (for the remaining sieve sizes),
2. Cold-feed gradation of coarse aggregates,
3. Extraction tests (for the remaining sieve sizes), and
4. Marshall properties.

If it can be assumed that this approach is valid, then a total of 38 separate control charts and separate tabulated results must be maintained, as given in Tables 2 (10, p. 96) and 3 (10, p. 98).

It should be noted that, once the control limits for each characteristic have been determined, the maintenance of the control charts is a relatively simple task that only requires that a single point be placed on the chart after the required number of test results are obtained. Even with this simplification in mind, the indicated requirements of documentation clearly become a factor to be reckoned with by the producer.

To put this problem in its proper perspective, however, it must also be noted that several other complicating factors also enter the picture. The first is that the level of documentation discussed above only applies to one mix; if several mixes are produced in the same period, the requirements are greatly compounded. In addition, the fact that testing must be done on a random basis requires the development of random schedules for each test for each mix. In a practical situation in which day-to-day problems arise, this could present a major bookkeeping problem for the technician. The final factor that must be considered is that the process control plan must be developed in conjunction with the acceptance testing requirements of PennDOT. Ideally, separate lot and sublot designations must therefore be kept for acceptance and process control characteristics.

Need for Guidance

We are not suggesting that PennDOT's bituminous specification requires such an extensive process control system. PennDOT's basic philosophy is that the details of the process control plan should be defined by the contractor or the material supplier. What is suggested in Tables 2 and 3, however, is that it is quite possible for a contractor or material supplier, with no available guidance, to assume that there is a need to maintain as many as 38 control charts and 24 tabulated characteristics for each type of mix. If the above information identifies the need for the industry as a whole, through its associations, to give some very serious consideration to what the guidelines for process control should be, we will have achieved our objective.

EXAMPLES OF PROCESS CONTROL PLANS SUBMITTED

If the ideal process control plan discussed in the previous section can be considered an extreme case, then current practices can be compared with this case by briefly discussing several actual plans that were submitted by bituminous suppliers who had contracted for projects under PennDOT's restricted performance specifications.

Plan A

One material supplier reacted to PennDOT's guidelines and requirements by submitting a plan that was a verbatim reproduction of the suggested guidelines. He supplied no specific details of the type given in the ideal

Table 1. Proposed process control frequency schedule for plant producing ID-2A wearing course material.

Characteristic	Frequency of Sampling and Testing
Extraction (n = 1)	Every 544 Mg[a]
Asphalt content	
Mix gradation	
Marshall criteria (n = 1)	Every 544 Mg[a]
Stability	
Flow	
Voids	
VFA	
Hot-bin gradation (n = 2)	Every 363 Mg[b]
Individual bins	
Combined bins	
Cold-feed gradation (n = 2), individual bins	Every 544 Mg
Completed mix temperature[c] (n = 3)	Every three trucks

Note: 1 Mg = 1.1 tons.

[a] Frequency defined by specification (2).

[b] Minimum frequency in specification is 1 test/544-Mg sublot.

[c] Subgroup consists of three temperature readings, one taken from each of three consecutive trucks.

Table 2. Proposed process control activities using control charts.

Process Control Activity	Number of Characteristics	Charts	
		Type	Number
Completed mix temperature	1	$\bar{X}$, R (n = 3)	2
Hot-bin gradation			
Combined bins	8	$\bar{X}$, R (n = 2)	16
Individual bins			
Bin 2, 2.38-mm sieve	1	$\bar{X}$, R, $\bar{X}_3$ (n = 2)	3
Bin 1			
0.075-mm sieve	1	$\bar{X}$, R (n = 2)	2
2.38-mm sieve	1	$\bar{X}$, R (n = 2)	2
Cold-feed gradation			
Coarse aggregate, 2.38-mm sieve	1	$\bar{X}$, R (n = 2)	2
Fine aggregate			
0.075-mm sieve	1	$\bar{X}$, R (n = 2)	2
2.38-mm sieve	1	$\bar{X}$, R (n = 2)	2
Extraction analysis			
Asphalt content	1	X, R, $\bar{X}_5$ (n = 1)	3
Gradation			
0.075-mm sieve	1	X, R (n = 1)	2
2.38-mm sieve	1	X, R (n = 1)	2
Total	18		38

Notes: 2.38- and 0.075-mm sieves = no. 8 and no. 200 sieves respectively.
Shewhart control charts are identified as $\bar{X}$, trend indicator charts as $\bar{X}_i$, and charts for individuals as X.

Table 3. Proposed process control activities using tabulation techniques.

Process Control Activity	Number of Characteristics	Type of Tabulation
Individual hot-bin gradations		
Bin 2 (4.75- and 9.52-mm sieves)	2	$\bar{X}$, R (n = 2)
Bin 1 (0.15-, 0.3-, 0.6-, 1.18-, and 4.75-mm sieves)	5	$\bar{X}$, R (n = 2)
Cold-feed gradations		
Coarse aggregate (4.75- and 9.52-mm sieves)	2	$\bar{X}$, R (n = 2)
Fine aggregate (0.15-, 0.3-, 0.6-, 1.18-, and 4.75-mm sieves)	5	$\bar{X}$, R (n = 2)
Extraction gradations (0.15-, 0.3-, 0.6-, 1.18-, 4.75-, and 9.52-mm sieves)	6	X, R (n = 1)
Marshall properties (stability, flow, voids, voids filled with asphalt)	4	X, R (n = 1)
Total	24	

Note: 0.15-, 0.3-, 0.6-, 1.18-, 4.75-, and 9.52-mm sieves = no. 100, no. 50, no. 30, no. 16, no. 4, and 0.375-in sieves respectively.

process control plan (Tables 1, 2, and 3) and therefore provided no basis on which his plan could realistically be evaluated. It might, therefore, be assumed that he either (a) developed a workable plan but was not willing to share this information with PennDOT or (b) gave very little thought to process control planning because he was not convinced that it could provide him with financial benefits.

Plan B

Another plan indicated the frequencies for each test but did not specify the size of the process characteristic sublot, the subgroup size, the randomizing process, or the types of control charts that would be used. The following example for the bituminous mixture tests indicates how these factors were conveniently glossed over:

1. Ross count is run every year before production is started. Ross count figures are on hand in district office for your inspection. The necessary mixing time was found to be 30 s/wet cycle time.
2. Aggregate gradation extraction method will be the immerex method. The aggregate gradation will be found from this test method, and a work sheet will be kept with the plant inspector for PennDOT inspection. Graphs will be kept for aggregate gradation and will be on file at the asphalt plant.
3. Bitumen content will be found from the extraction test and plotted on graph paper and kept on file at the plant.
4. We will be shooting for a mixing temperature of 149°C (300°F). Temperatures will be taken every fifth load to ensure proper mixing temperature control.

It should again be pointed out that if such a plan were accepted very little information would be supplied to PennDOT that would allow an evaluation of the adequacy of the process control system to be used.

Plan C

Plan C, as shown in the excerpt for bituminous mixtures reproduced below, attempts to supply some of the information required. Note, however, that such details as size of sublot, size of subgroups, and method of evaluating the UCL and LCL are still missing:

A. Percentage bitumen (one per sublot, plot value)
  1. Sampling location—off truck
  2. Truck to be sampled determined by PTM 1, Table 2 (tonnage)
B. Aggregate gradation
  1. Taken from same sample used to determine percentage bitumen
  2. Plot all values (sieves)
C. Marshall properties
  1. Sample taken from same truck as sample for determining percentage bitumen
  2. Average of three molds—plot
    (a) Stability
    (b) Flow
    (c) Percentage voids
    (d) Percentage voids filled with asphalt
D. Mixing temperature—Two tests taken on first five trucks each day, then two tests on every third truck thereafter
E. Ross counts taken at beginning of job to determine mixing time and additional taken at any time it would become visibly necessary

Plan D

After revisions suggested by PennDOT were included, plan D provided the following description for the bituminous mixture and documentation portions.

Bituminous Mixture

1. Ross counts will be taken at the start to confirm

mix time in accordance with PTM 736 and also when mix time is changed or when an amount of uncoated stone can be seen on a loaded truck.

2. A sample of completed mixtures will be taken and extracted at random and in accordance with our process control system and for acceptance.
3. Mixing temperatures will be obtained from our inspected asphalt affidavit and will be maintained within the tolerance limits stated in form 408.
4. Truck temperatures will be taken on the first three trucks of the day and every third truck thereafter for the entire sublot.

Documentation

Straight-line analysis charts will be kept on all raw aggregates, hot-bin gradations, and extractions. Hot-bin gradations and extractions will be taken once per sublot. Sieve sizes will be kept on charts [for hot bins according to PennDOT specification (1, Table 401-1)].

Item	Sieve Sizes (mm)
Raw aggregate	
Fine aggregate	0.074, 0.15, 0.3, 0.6, 1.18, 2.36, 4.75, 9.52
1-B limestone	2.36, 4.75, 9.52, 12.5
1-B gravel	
2-B limestone	2.36, 4.75, 9.52, 12.5, 19, 25
Hot bins	
Binder	0.074, 0.15, 0.3, 0.6, 1.18, 2.36, 4.75, 12.5, 25
Wearing	0.074, 0.15, 0.3, 0.6, 1.18, 2.36, 4.75, 9.52, 12.5
200 mesh (to be determined by PTM 100)	

Evaluation

Some of the specific details alluded to in the earlier plans are also missing in plan D. The notation regarding documentation, for instance, notes that "straight-line" analysis charts will be kept for various material characteristics. It must be assumed that the subgroup size of n = 1 will be used throughout although, as noted in the discussion of the ideal plan, subgroups of size n = 2 or 3 provide a better indication of the true nature of the capability of the process. An indication of how the UCL and LCL will be determined is also missing from the plan.

SUMMARY

The ideal process control plan discussed in this paper is clearly unrealistic from the standpoint of documentation. Examples of submitted process control plans are also clearly deficient because they do not indicate that the correct statistically based process control decisions have been made. A need for additional guidance to individual contractors and material suppliers is thus indicated. If the process control plan is to clearly outline a system that will aid these parties, more information must appear in the literature regarding this facet of statistically based quality assurance specifications. In fact, it might be stated that, if these types of specifications are to gain wider adoption and support in the future, it is necessary that the benefits that have been achieved by use of well-defined process control plans must be shared within the industry.

ACKNOWLEDGMENT

The contents of this paper reflect our views, and we are responsible for the facts and the accuracy of the data presented. The contents do not necessarily reflect the official views or policies of the Pennsylvania Department of Transportation or the Federal Highway Administration. This paper does not constitute a standard, specification, or regulation.

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Development of a Highway Construction Acceptance Plan

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Acceptance plans are being developed for highway construction inspection that require that the quality of a lot submitted by a contractor for acceptance be estimated by calculating the percentage that meets specification limits. This type of acceptance plan was initially developed in the early 1950s for use in Military Standard 414 for the inspection by variables of government procurement. The theory that underlies such acceptance plans is presented. Tables developed to facilitate the estimation of lot quality from small sample sizes are given. Four cases are considered: (a) Population mean $\overline{X}'$ and population standard deviation σ' are both known, (b) $\overline{X}'$ is known and σ' is unknown, (c) $\overline{X}'$ is unknown and σ' is known, and (d) $\overline{X}'$ and σ' are both unknown. In the fourth case, the one that most often applies in construction situations, two methods of estimation are possible: the range method and the standard deviation method. Although the range method has been used exclusively in highway construction, it is suggested that consideration be given to using the standard deviation method.

This paper presents the development of percentage within specification limits (PWL) tables for acceptance plans that require that an estimate be made of the percentage of submitted material that meets specification limits. One advantage of such acceptance plans is that the estimate of quality that is used is a more meaningful and concise index than either central tendency or central tendency and dispersion, two indexes that have been used almost exclusively in other acceptance plans. Central tendency, of course, tells nothing about the variability of the material and is therefore limited in its application in highway construction to those rare cases in which it can be assumed that the variability is known. Central tendency and dispersion, on the other hand, must be evaluated together in order to adequately describe the material in question; however, any comparison among several lots of different quality requires that these two measures be converted into a single percentage that meets specification limits.

Many highway agencies have been reluctant to adopt the PWL type of acceptance plan. A primary reason appears to be that specification writers do not have at their disposal a clearly defined path through the development of the underlying theory. The basic acceptance tables can be found in Military Standard 414 (1), but this standard presents the end product rather than the developmental rationale that is needed to fully understand the acceptance plans.

The purpose of this paper, therefore, is to summarize the theory that underlies the PWL type of acceptance plan to make it more convenient for those who might be interested in incorporating such a plan into their specifications. This paper should assist specification writers by filling the gaps that presently exist and thereby make it possible for adaptations of Military Standard 414 to highway construction to reach their maximum potential. A complete discussion of these acceptance plans can be found elsewhere (2, 3, 4).

ESTIMATION OF PWL

In estimating the quality of a lot of material, four cases can be considered. These cases are a function of the amount of information that is known or that can be assumed about the lot of material being submitted by a contractor or material supplier for acceptance. These cases may be listed as follows:

1. Population mean $\overline{X}'$ and population standard deviation σ' are known,
2. $\overline{X}'$ is known and σ' is unknown,
3. $\overline{X}'$ is unknown and σ' is known, and
4. $\overline{X}'$ and σ' are both unknown.

Military Standard 414 refers only to cases 3 and 4. Although case 4 is by far the most common in highway construction, the development of an estimate of quality is more complicated in this case because two parameters are unknown. Case 4 can best be understood if the theory is presented in steps starting with the simpler case 1.

Case 1

Case 1 presents no problem in highway construction because if $\overline{X}'$ and σ' are both known there is no need for an acceptance plan. In other words, if one knew the contractor's or material supplier's $\overline{X}'$ and σ', there would be no need to take a sample because the quality of the lot could easily be calculated. Assuming that the random variable (i.e., the quality characteristic) is normally distributed, the percentage meeting the specification limits is simply 100 percent minus the percentage of area under the normal distribution curve that is outside the lower specification limit L or outside the upper specification limit U or both. Thus, for double-limit specifications,

$$\mathrm{PWL}' = 100 - 100\left[\int_{-\infty}^{(L-\overline{X}')/\sigma'} f(z)dz\right] - 100\left[\int_{(U-\overline{X}')/\sigma'}^{+\infty} f(z)dz\right] \quad (1)$$

where $f(z)$ = standard normal density = $(1/2\sqrt{\pi})\exp(-z^2/2)$ or

$$(\mathrm{PWL}'/100) = 1 - \left[\int_{-\infty}^{(L-\overline{X}')/\sigma'} f(z)dz + \int_{(U-\overline{X}')/\sigma'}^{+\infty} f(z)dz\right] \quad (2)$$

Note that in this case a prime appears above the PWL notation to denote a population parameter. In all other cases, the PWL notation without the prime is used.

As an example of the use of Equation 2, it is assumed that a lot of bituminous concrete has a mean asphalt content $\overline{X}'$ = 6.0 percent with a standard deviation σ' = 0.25 percent. If asphalt contents between L = 5.6 percent and U = 6.4 percent meet the specification limits, then Equation 2 can be used to find the actual percentage of the lot that meets specification limits. Thus,

$$\mathrm{PWL}'/100 = 1 - \left[\int_{-\infty}^{(5.6-6.0)/0.25} f(z)dz + \int_{(6.4-6.0)/0.25}^{+\infty} f(z)dz\right] \quad (3)$$

Thus, PWL'/100 = 1 - (0.0548 + 0.0548) = 0.8904, or PWL' = 89.04 percent.

Case 2

When $\overline{X}'$ is known but σ' is unknown, sampling inspec-

Table 1. Factors for making unbiased estimates of $\overline{\sigma}$ or $\overline{R}$.

Number of Observations in Subgroup n'	c_2 Factor	d_2 Factor	Number of Observations in Subgroup n'	c_2 Factor	d_2 Factor
2	0.5642	1.128	14	0.9353	3.407
3	0.7236	1.693	15	0.9490	3.472
4	0.7979	2.059	16	0.9523	3.532
5	0.8407	2.326	17	0.9551	3.588
6	0.8686	2.534	18	0.9576	3.640
7	0.8882	2.704	19	0.9599	3.689
8	0.9027	2.847	20	0.9619	3.735
9	0.9139	2.970	25	0.9696	3.931
10	0.9227	3.078	30	0.9748	4.086
11	0.9300	3.173	50	0.9849	4.498
12	0.9359	3.258	100	0.9925	5.015
13	0.9410	3.336			

Table 2. d_2^* factor for various numbers of subgroups of size n'.

Number of Subgroups of Size $n' = 5$	d_2^* Factor	Number of Subgroups of Size $n' = 5$	d_2^* Factor
1	2.474	8	2.346
2	2.405	10	2.342
3	2.379	12	2.339
5	2.358	20	2.334
6	2.353	35	2.331
7	2.349	∞	$2.326 = d_2$

tion is necessary to obtain an estimate of the quality of a lot. Since the only unknown term on the right side of Equation 2 is σ', the first inclination might be to estimate σ' from the sample data and substitute that estimate into Equation 2. It is not that easy, however, because the value of standard deviation or range that would be obtained from a small sample (i.e., $n < 30$) would provide a biased estimate of σ'. It has been shown (5, pp. 350-352) that the sample standard deviation $s = \sqrt{\Sigma\,(X - \overline{X})^2/(n-1)}$, the root-mean-square deviation $\sigma = \sqrt{\Sigma\,(X - \overline{X})^2/n}$, and the sample range R are all biased estimators of σ'.

To correct for this bias, one might use a table similar to Table 1 (5, p. 644). In Table 1, c_2 ($\sigma' = \overline{\sigma}/c_2$) is the unbiasing factor associated with the range. To use the table, one must understand that a sample (of size $n > 1$) can be thought of as consisting of one subgroup of size n or several subgroups of size n'. If m equals the number of subgroups, then $n = mn'$. The use of more than one subgroup is sometimes advantageous, especially if the sample range R is used to estimate σ'. The unbiased estimates can be based on calculating σ, s, or R from the entire sample when only one subgroup is available or on calculating $\overline{\sigma}$, $\overline{s}$, or $\overline{R}$ (i.e., the average σ, s, or R obtained from m individual subgroups). The unbiased estimates of σ' can therefore be σ/c_2, $s/c_2\sqrt{n/(n-1)}$, or R/d_2 whenever the sample consists of one subgroup of size n, or they can be $\overline{\sigma}/c_2$, $\overline{s}/c_2\sqrt{n'/(n'-1)}$, or $\overline{R}/d_2$ when m subgroups of size n' are used.

It should be noted that the factor to be used in making estimates from the sample range (R or $\overline{R}$) must be chosen with caution. Although d_2 ($\sigma' = \overline{R}/d_2$) is the correct unbiasing factor, it has been found that for a small number of subgroups (i.e., $m < 20$) a slightly larger factor (d_2^*) will give better precision even though the estimate of σ' will be somewhat biased. Although Military Standard 414 uses the symbol c in place of d_2^*, the d_2^* designation is used by most statisticians and is used in this paper.

Unlike d_2, d_2^* varies with the number of subgroups. Data given in Table 2 (5, p. 93) show the effect of the number of subgroups on d_2^* for a subgroup of size $n' = 5$.

Note in Table 2 that d_2^* becomes essentially a constant (d_2) when the sample contains about 20 or more subgroups.

It should also be noted that, although the c_2 and d_2 factors given in Table 1 correct the bias in the estimate of σ', the mere substitution of an unbiased estimate of σ' in Equation 2 does not result in an unbiased estimate of PWL′. (This can be seen in Equation 1. If the true value of σ' in a certain situation is 3, for instance, the average PWL′ obtained by using σ' estimates of 2, 3, and 4 is not equal to the PWL′ obtained with $\sigma' = 3$.) Although it is biased, the estimate of PWL′ obtained through the substitution for σ' is nonetheless a good estimate. The unbiased estimate of σ' that is preferred for the substitution into Equation 2 is σ/c_2 (or $\overline{\sigma}/c_2$) since σ is the maximum likelihood estimate of σ' (6, p. 257). In the case of one subgroup of size n that represents a particular lot of material, the estimated PWL can thus be obtained by using the following equation, which is analogous to Equation 2:

$$\mathrm{PWL}/100 = 1 - \left[\int_{-\infty}^{c_2(L-\overline{X}')/\sigma} f(z)dz + \int_{c_2(U-\overline{X}')/\sigma}^{+\infty} f(z)dz\right] \tag{4}$$

As an example to demonstrate the use of Equation 4, it is assumed that an asphalt content sample of size $n = 5$ taken from a lot that has a known $\overline{X}'$ of 6.0 percent indicates a root-mean-square deviation $\sigma = 0.25$ percent. For a specification that has $L = 5.6$ percent and $U = 6.4$ percent, the estimated quality then becomes

$$\mathrm{PWL}/100 = 1 - \left[\int_{-\infty}^{0.8407(5.6-6.0)/0.25} f(z)dz + \int_{0.8407(6.4-6.0)/0.25}^{+\infty} f(z)dz\right] \tag{5}$$

Thus, $\mathrm{PWL}/100 = 1 - (0.0885 + 0.0885) = 0.8230$, or $\mathrm{PWL} = 82.30$ percent.

It should be noted that a sample statistic $c_2\,(L - \overline{X}')/\sigma$ or $c_2(U - \overline{X}')/\sigma$ must be calculated to obtain the estimate. This sample statistic follows a normal distribution; however, as will be seen in case 4, not all sample statistics provide this convenience. Further, it should be noted that the Equation 4 estimate is a function of σ (since σ is the only unknown term and is calculated from sample data). As indicated, other estimates are possible—for example, those that are a function of s or R. No matter which estimate is used, however, the only information to be used from the sample data in case 2 is a measure of variability.

Case 3

As in case 2, numerous equations are possible for estimating PWL′ when σ' is known. All of these estimates should be based on a sample statistic that is a function of central tendency. The statistic selected for use in Military Standard 414 is $\sqrt{n/(n-1)}\;(L - \overline{X})/\sigma'$ or $\sqrt{n/(n-1)}\;(U - \overline{X})/\sigma'$. Additional information regarding the development of this statistic is available elsewhere (7). As the statistic is developed, the best estimate of PWL′ when $\overline{X}'$ is unknown and σ' is known can be expressed as

$$\mathrm{PWL}/100 = 1 - \left[\int_{-\infty}^{\sqrt{n/(n-1)}\,(L-\overline{X})/\sigma'} f(z)dz + \int_{\sqrt{n/(n-1)}\,(U-\overline{X})/\sigma'}^{+\infty} f(z)dz\right] \tag{6}$$

Figure 1. Symmetrical beta distributions ($\alpha = \beta$).

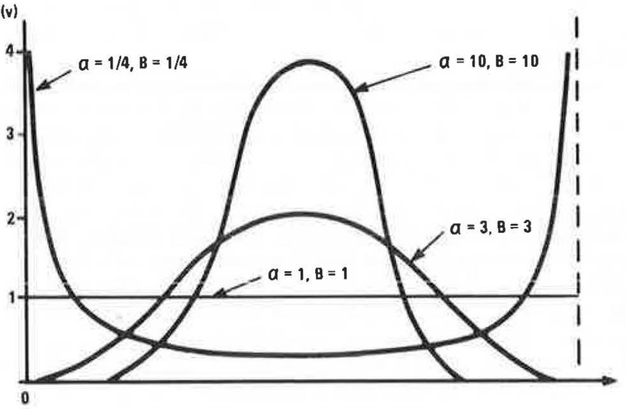
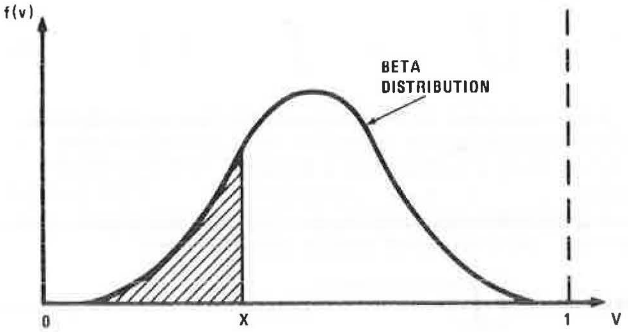


Figure 2. Incomplete beta function ratio.



$$I_X(\alpha, \beta) = \frac{\text{shaded area}}{\text{area under Beta distribution (equals 1)}}$$

Table 3. Incomplete beta function ratio I_x (α, β) for parameters of standard deviation method.

x^a	$\alpha = \beta = 0.5$ (n = 3)	$\alpha = \beta = 1.0$ (n = 4)	$\alpha = \beta = 1.5$ (n = 5)	$\alpha = \beta = 2.0$ (n = 6)	$\alpha = \beta = 2.5$ (n = 7)
0.01	0.063 768 6	0.010 000 0	0.001 692 6	0.000 298 0	0.000 053 7
0.02	0.090 334 5	0.020 000 0	0.004 772 8	0.001 184 0	0.000 300 7
0.03	0.110 824 7	0.030 000 0	0.008 741 4	0.002 646 0	0.000 819 8
0.04	0.128 188 4	0.040 000 0	0.013 417 1	0.004 672 0	0.001 664 5
0.05	0.143 566 3	0.050 000 0	0.018 693 0	0.007 250 0	0.002 875 8
0.06	0.157 542 4	0.060 000 0	0.024 496 3	0.010 368 0	0.004 486 1
0.07	0.170 463 4	0.070 000 0	0.030 772 2	0.014 014 0	0.006 521 8
0.08	0.182 554 9	0.080 000 0	0.037 478 0	0.018 176 0	0.009 004 2
0.09	0.193 973 4	0.090 000 0	0.044 578 4	0.022 842 0	0.011 950 6
0.10	0.204 832 8	0.100 000 0	0.052 044 0	0.028 000 0	0.015 374 7
0.11	0.215 219 0	0.110 000 0	0.059 849 4	0.033 638 0	0.019 267 6
0.12	0.225 198 9	0.120 000 0	0.067 972 4	0.039 744 0	0.023 697 5
0.13	0.234 825 5	0.130 000 0	0.076 393 4	0.046 306 0	0.028 610 3
0.14	0.244 141 8	0.140 000 0	0.085 094 6	0.053 312 0	0.034 029 9
0.15	0.253 183 3	0.150 000 0	0.094 060 2	0.060 750 0	0.039 958 3
0.16	0.261 979 8	0.160 000 0	0.103 275 5	0.068 608 0	0.046 395 9
0.17	0.270 556 3	0.170 000 0	0.112 727 0	0.076 874 0	0.053 341 1
0.18	0.278 934 3	0.180 000 0	0.122 402 3	0.085 536 0	0.060 791 3
0.19	0.287 132 6	0.190 000 0	0.132 289 7	0.094 582 0	0.068 742 2
0.20	0.295 167 2	0.200 000 0	0.142 378 5	0.104 000 0	0.077 188 6
0.21	0.303 052 5	0.210 000 0	0.152 658 3	0.113 778 0	0.086 123 8
0.22	0.310 801 1	0.220 000 0	0.163 119 4	0.123 904 0	0.095 540 2
0.23	0.318 424 2	0.230 000 0	0.173 752 7	0.134 366 0	0.105 429 1
0.24	0.325 931 9	0.240 000 0	0.184 549 4	0.145 152 0	0.115 780 9
0.25	0.333 333 3	0.250 000 0	0.195 501 1	0.156 250 0	0.126 585 0
0.26	0.340 636 7	0.260 000 0	0.206 599 9	0.167 648 0	0.137 830 1
0.27	0.347 849 4	0.270 000 0	0.217 838 1	0.179 334 0	0.149 504 1
0.28	0.354 978 4	0.280 000 0	0.229 208 1	0.191 296 0	0.161 594 0
0.29	0.362 030 1	0.290 000 0	0.240 703 0	0.203 522 0	0.174 086 4
0.30	0.369 010 1	0.300 000 0	0.252 315 8	0.216 000 0	0.186 967 0
0.31	0.375 924 0	0.310 000 0	0.264 039 7	0.228 718 0	0.200 220 9
0.32	0.382 776 7	0.320 000 0	0.275 868 2	0.241 664 0	0.213 832 8
0.33	0.389 572 9	0.330 000 0	0.287 795 0	0.254 826 0	0.227 786 8
0.34	0.396 317 1	0.340 000 0	0.299 813 9	0.268 192 0	0.242 066 4
0.35	0.403 013 3	0.350 000 0	0.311 918 8	0.281 750 0	0.256 654 8
0.36	0.409 665 5	0.360 000 0	0.324 103 8	0.295 488 0	0.271 534 7
0.37	0.416 277 4	0.370 000 0	0.336 363 1	0.309 394 0	0.286 688 4
0.38	0.422 852 6	0.380 000 0	0.348 691 0	0.323 456 0	0.302 097 7
0.39	0.429 394 3	0.390 000 0	0.361 081 8	0.337 662 0	0.317 744 4
0.40	0.435 905 8	0.400 000 0	0.373 530 0	0.352 000 0	0.333 609 6
0.41	0.442 390 2	0.410 000 0	0.386 030 3	0.366 458 0	0.349 674 4
0.42	0.448 850 6	0.420 000 0	0.398 577 1	0.381 024 0	0.365 919 5
0.43	0.455 289 7	0.430 000 0	0.411 165 2	0.395 686 0	0.382 325 5
0.44	0.461 710 5	0.440 000 0	0.423 789 4	0.410 432 0	0.398 872 6
0.45	0.468 115 7	0.450 000 0	0.436 444 3	0.425 250 0	0.415 541 1
0.46	0.474 508 0	0.460 000 0	0.449 124 8	0.440 128 0	0.432 311 0
0.47	0.480 889 9	0.470 000 0	0.461 825 7	0.455 054 0	0.449 162 0
0.48	0.487 264 2	0.480 000 0	0.474 542 0	0.470 016 0	0.466 074 1
0.49	0.493 633 4	0.490 000 0	0.487 268 5	0.485 002 0	0.483 026 9
0.50	0.500 000 0	0.500 000 0	0.500 000 0	0.500 000 0	0.500 000 0

[a] The value I_x (α, β) for x greater than 0.50 is the complement of that for 1 - x. For example, when $\alpha = \beta = 2.5$, the value of I_x (α, β) for 0.61 is obtained by subtracting the value 0.317 744 4 for 0.39 from 1; i.e., 1 - 0.317 744 4 = 0.682 255 6.

where PWL is an estimate that is a function of the sample mean $\overline{X}$.

Equation 6 is very similar to Equation 2, the most obvious difference being the $\sqrt{n/(n-1)}$ factor, which is introduced in Equation 6 because $\overline{X}'$ is not known but is estimated by $\overline{X}$. The larger the sample, the better is the estimate of $\overline{X}$. Hence, as n approaches ∞, $\sqrt{n/(n-1)}$ tends to become 1. It may also be noted that Equation 6 is also similar to Equation 4.

As an example to show the use of Equation 6, it is assumed that an asphalt content sample of size n = 5, taken from a lot that has a known σ' of 0.25 percent, shows a sample mean $\overline{X} = 6.0$ percent. For a specification that has L = 5.6 percent and U = 6.4 percent, the estimated quality then becomes

$$PWL/100 = 1 - \left[\int_{-\infty}^{1.118(5.6-6.0)/0.25} f(z)dz + \int_{1.118(6.4-6.0)/0.25}^{+\infty} f(z)dz\right] \qquad (7)$$

Thus, PWL/100 = 1 - (0.0367 + 0.0367) = 0.9266 or PWL = 92.66 percent.

Case 4

The above discussion has set the pattern for case 4. As in cases 2 and 3, to obtain an estimate of PWL′ a sample of size n > 1 must be taken on which measurements of a quality characteristic are made. A statistic that is known to follow a certain distribution is then computed. The estimate of PWL′ can then be obtained by finding the appropriate area under the distribution being considered.

In accordance with the procedure outlined in Military Standard 414, two methods of estimating quality are presented for case 4: (a) the standard deviation method and (b) the range method. It is important to realize before these two methods are discussed that the normal distribution cannot be used in case 4 since matters have become more complicated now that $\overline{X}'$ and σ' are both unknown. As developed elsewhere (7), the sample statistics that are used to provide the best estimate of PWL′ in this case follow a symmetrical beta distribution. An explanation of the reason for using the beta distribution can be found in a paper by Lieberman and Resnikoff (8). The discussion that follows will provide a brief introduction to the beta distribution and will also provide a table of this distribution, which is often difficult to obtain.

A random variable v is said to be distributed as the beta distribution if the density function is given by

$$f(v) = [\Gamma(\alpha + \beta)/\Gamma(\alpha)\Gamma(\beta)]\, v^{\alpha-1}(1 - v)^{\beta-1} \qquad 0 \leqslant v \leqslant 1 \qquad (8)$$

with parameters α and β, both of which are positive constants. When α is equal to β, the distribution is symmetric as shown in Figure 1.

Figure 3. Representation of the estimate of PWL′ using double specification limits when PWL is a function of $\bar{X}$ and s ($\bar{X}'$ and σ' unknown).

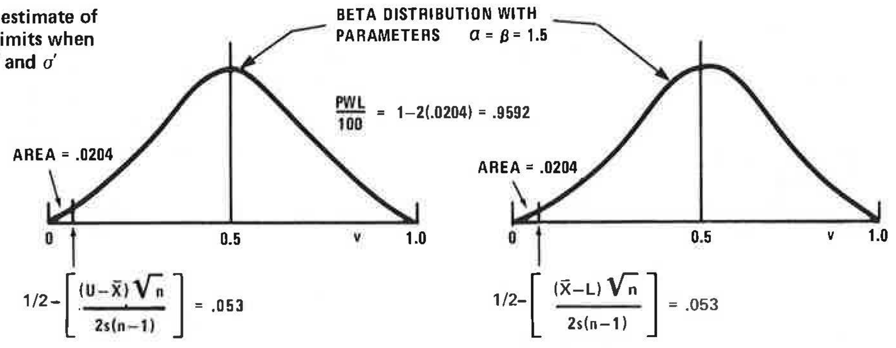


Table 4. Values of d_2^* and ν for use in range method estimate of case 4.

Subgroups (m)	Factor	Size of Subgroups (n′) 2	3	4	5	6	7	8	9	10	15
1	d_2^*	1.41	1.91	2.24	2.48	2.67	2.83	2.96	3.08	3.18	3.55
	ν	1.00	1.98	2.93	3.83	4.68	5.48	6.25	6.98	7.68	10.8
2	d_2^*	1.28	1.81	2.15	2.40	2.60	2.77	2.91	3.02	3.13	3.51
	ν	1.92	3.83	5.69	7.47	9.16	10.8	12.3	13.8	15.1	21.3
3	d_2^*	1.23	1.77	2.12	2.38	2.58	2.75	2.89	3.01	3.11	3.50
	ν	2.82	5.66	8.44	11.1	13.6	16.0	18.3	20.5	22.6	31.9
4	d_2^*	1.21	1.75	2.11	2.37	2.57	2.74	2.88	3.00	3.10	3.49
	ν	3.71	7.49	11.2	14.7	18.1	21.3	24.4	27.3	30.1	42.4
5	d_2^*	1.19	1.74	2.10	2.36	2.56	2.73	2.87	2.99	3.10	3.49
	ν	4.59	9.31	13.9	18.4	22.6	26.6	30.4	34.0	37.5	52.9

Γ in Equation 8 is the symbol for a gamma function. The gamma function $\Gamma(A)$ is defined by

$$\Gamma(A) = \int_0^\infty x^{A-1} e^{-x} dx \quad A > 0 \tag{9}$$

It can be shown—as, for example, by Miller (9)—that if A is a positive integer, $\Gamma(A) = (A-1)!$. If B is a positive half-integer greater than 1 (i.e., 1.5, 2.5, 3.5, and so on), one may write $B = m + 0.5$ where m is an integer, and it can be shown that $\Gamma(B) = (B-1), (B-2), (B-3), \ldots, (B-m)\,\Gamma(0.5)$ where $\Gamma(0.5) = \pi$.

In working with the beta distribution, the incomplete beta function ratio is normally used. The incomplete beta function ratio $I_x(\alpha, \beta)$ is defined by

$$I_x(\alpha,\beta) = [\Gamma(\alpha+\beta)/\Gamma(\alpha)\Gamma(\beta)] \int_0^x v^{\alpha-1}(1-v)^{\beta-1} dv \tag{10}$$

As Figure 2 shows, the incomplete beta function ratio gives an area under the beta distribution from $v = 0$ to $v = x$.

$I_x(\alpha, \beta)$ has been tabulated by Pearson (10) for α and β values of integers and half-integers less than or equal to 50. Although Pearson's tables are extensive, only values of $\alpha = \beta$ are required to solve the equations that apply for case 4. It will be shown below that the parameters α and β of the beta distributions developed for the standard deviation method are $(n/2) - 1$; therefore, α and β are always half-integers for that method.

Table 3 (10) is a table of the incomplete beta function ratio for the standard deviation method parameters. Table 3 was obtained from Pearson's tables. Only those beta distributions that are required for n = 3 through n = 7 are tabulated.

Standard Deviation Method

The equation for estimating PWL′ by using the standard deviation method of case 4 is

$$PWL/100 = 1 - \left(\int_0^{\max\{0,(1/2) - [(U-\bar{X})\sqrt{n}/2s(n-1)]\}} d\beta[(n/2)-1] + \int_0^{\max\{0,(1/2) - [(\bar{X}-L)\sqrt{n}/2s(n-1)]\}} d\beta[(n/2)-1] \right) \tag{11}$$

where PWL is an estimate that is a function of both $\bar{X}$ and s and $d\beta\,[(n/2) - 1]$ is a symmetrical beta density function with parameters α and β both equal to $[(n/2) - 1]$.

A symmetrical beta distribution that has parameters α and β greater than 1 (i.e., $n > 4$) is similar in appearance to the normal distribution (Figure 1); however, whereas the normal random variable z is continuous over an infinite range, the beta random variable v is continuous over a range from 0 to 1. Figure 3 shows the estimate of PWL′ obtained by means of Equation 11 for the case of an asphalt content sample of size n = 5 that yields a sample mean $\bar{X} = 6.0$ percent and a sample standard deviation s = 0.25 percent for a specification that has L = 5.6 percent and U = 6.4 percent. This estimate is

$$PWL/100 = 1 - \left[\int_0^{\max(0,0.053)} d\beta(1.5) + \int_0^{\max(0,0.053)} d\beta(1.5) \right] \tag{12}$$

Thus, PWL/100 = 1 - (0.0204 + 0.0204) = 0.9592, or PWL = 95.92 percent.

Range Method

The equation for estimating PWL′ by using the range method of case 4 is

$$PWL/100 = 1 - \left(\int_0^{\max\{0,(1/2)-[d_2^*(U-\bar{X})\sqrt{\nu+1}/2\bar{R}\nu]\}} d\beta\{[(\nu+1)/2]-1\} + \int_0^{\max\{0,(1/2)-[d_2^*(\bar{X}-L)\sqrt{\nu+1}/2\bar{R}\nu]\}} \times d\beta\{[(\nu+1)/2]-1\} \right) \tag{13}$$

where PWL is an estimate that is a function of both $\overline{X}$ and $\overline{R}$, $d\beta\ \{[(\nu+1)/2]-1\}$ is a beta density function with parameters of α and β both equal to $[(\nu+1)/2]-1$, and

$d_2^* =$ factor from Table 2 or Table 4;
$\nu =$ degrees of freedom [see Table 4, modified from Nelson (11)]; and
$\overline{R} =$ average range of subgroups ($\overline{R} = R$ where only one subgroup is used).

Table 5. Incomplete beta function ratio I_x (α, β) for parameters of range method.

x^a	$\alpha=\beta=0.467$ (n = 3) .	$\alpha=\beta=0.998$ (n = 4)	$\alpha=\beta=1.414$ (n = 5)	$\alpha=\beta=1.84$ (n = 6)	$\alpha=\beta=2.25$ (n = 7)
0.01	0.072 396 8	0.010 072 5	0.002 289 5	0.000 517 9	0.000 126 3
0.02	0.100 241 0	0.020 117 2	0.006 086 0	0.001 843 9	0.000 595 3
0.03	0.121 347 6	0.030 151 7	0.010 771 1	0.003 866 8	0.001 469 4
0.04	0.139 038 2	0.040 179 6	0.016 137 0	0.006 520 6	0.002 782 2
0.05	0.154 580 0	0.050 202 5	0.022 069 3	0.009 788 1	0.004 555 8
0.06	0.168 616 2	0.060 221 7	0.028 487 8	0.013 612 5	0.006 804 9
0.07	0.181 525 6	0.070 237 6	0.035 336 2	0.017 974 1	0.009 539 4
0.08	0.193 553 5	0.080 251 1	0.042 571 0	0.022 849 0	0.012 765 7
0.09	0.204 868 9	0.090 262 2	0.050 156 5	0.028 215 2	0.016 487 4
0.10	0.215 594 7	0.100 271 2	0.058 063 7	0.034 052 9	0.020 705 7
0.11	0.225 823 0	0.110 278 5	0.066 267 7	0.040 343 7	0.025 420 3
0.12	0.235 625 3	0.120 284 2	0.074 747 3	0.047 070 4	0.030 628 9
0.13	0.245 058 1	0.120 388 4	0.083 483 6	0.054 216 6	0.036 328 1
0.14	0.254 107 2	0.140 291 3	0.092 400 0	0.061 766 9	0.042 513 3
0.15	0.202 990 1	0.150 293 1	0.101 661 6	0.069 706 4	0.049 178 7
0.16	0.271 558 4	0.160 293 8	0.111 074 9	0.078 020 9	0.056 318 0
0.17	0.279 898 4	0.170 293 4	0.120 687 5	0.086 696 6	0.063 923 4
0.18	0.288 032 9	0.180 292 1	0.130 488 3	0.095 720 1	0.071 986 9
0.19	0.295 981 3	0.190 289 9	0.140 466 6	0.105 078 4	0.080 499 8
0.20	0.303 761 0	0.200 286 9	0.150 612 9	0.114 759 0	0.089 452 3
0.21	0.311 386 4	0.210 283 2	0.160 918 0	0.124 749 5	0.098 834 7
0.22	0.318 871 0	0.220 278 7	0.171 373 4	0.135 037 8	0.108 636 3
0.23	0.326 226 5	0.230 273 7	0.181 971 1	0.145 612 1	0.118 846 1
0.24	0.333 463 3	0.240 268 0	0.192 703 5	0.156 460 9	0.129 452 7
0.25	0.340 591 0	0.250 261 7	0.203 563 3	0.167 572 7	0.140 444 0
0.26	0.347 618 0	0.260 254 9	0.214 543 6	0.178 936 2	0.151 808 1
0.27	0.354 552 2	0.270 247 6	0.225 638 1	0.190 540 5	0.163 532 1
0.28	0.361 400 5	0.280 239 8	0.236 840 3	0.202 374 5	0.175 603 3
0.29	0.368 169 7	0.290 231 7	0.248 144 2	0.214 427 6	0.188 008 4
0.30	0.374 865 6	0.300 223 0	0.259 544 0	0.226 689 0	0.200 734 0
0.31	0.381 493 9	0.310 214 0	0.271 033 9	0.239 148 2	0.213 766 2
0.32	0.388 059 7	0.320 204 7	0.282 608 9	0.251 794 8	0.227 091 1
0.33	0.394 567 9	0.330 195 1	0.294 263 4	0.264 618 4	0.240 694 5
0.34	0.401 022 9	0.340 185 1	0.305 992 3	0.277 608 7	0.254 561 9
0.35	0.407 428 9	0.350 174 8	0.317 790 7	0.290 755 6	0.268 678 8
0.36	0.413 790 1	0.360 164 3	0.329 653 6	0.304 049 0	0.283 030 3
0.37	0.420 110 3	0.370 153 5	0.341 576 5	0.317 478 8	0.297 601 5
0.38	0.426 392 9	0.380 142 5	0.353 554 5	0.331 035 0	0.312 377 3
0.39	0.432 641 5	0.390 131 2	0.365 583 1	0.344 707 7	0.327 342 6
0.40	0.438 859 4	0.400 119 9	0.377 658 0	0.358 487 2	0.342 481 9
0.41	0.445 049 8	0.410 108 3	0.389 774 6	0.372 363 3	0.357 779 6
0.42	0.451 215 6	0.420 096 6	0.401 928 4	0.386 326 6	0.373 220 4
0.43	0.457 359 9	0.430 084 7	0.414 115 4	0.400 367 0	0.388 788 5
0.44	0.463 485 4	0.440 072 9	0.426 331 3	0.414 475 0	0.404 468 1
0.45	0.469 595 2	0.450 060 8	0.438 571 9	0.428 640 8	0.420 243 4
0.46	0.475 691 7	0.460 048 7	0.450 832 9	0.442 854 8	0.436 098 7
0.47	0.481 777 7	0.470 036 5	0.463 110 3	0.457 107 3	0.452 017 9
0.48	0.487 856 0	0.480 024 2	0.475 400 0	0.471 388 8	0.467 985 2
0.49	0.493 929 2	0.490 011 9	0.487 697 8	0.485 689 5	0.483 984 5
0.50	0.500 000 0	0.500 000 0	0.500 000 0	0.500 000 0	0.500 000 0

[a] The value I_x (α,β) for x greater than 0.50 is the complement of that for 1 - x. For example, when $\alpha=\beta=2.25$, the value I_x (α,β) for 0.61 is obtained by subtracting the value 0.327 342 6 for 0.39 from 1; i.e., 1 - 0.327 342 6 = 0.672 657 4.

Table 5 (3, pp. 103-105), a table of the incomplete beta function ratio for some commonly used parameters of the range method, can now be used to solve the following example. If an asphalt content sample of size n = 5 yields a sample mean $\overline{X} = 6.0$ percent and a sample range R = 0.6 percent for a specification that has L = 5.6 percent and U = 6.4 percent, then an estimate of PWL′ can be computed from Equation 13. Using $\nu = 3.828$ and $d_2^* = 2.474$, the estimate becomes

$$PWL/100 = 1 - \left[\int_0^{\max(0,0.027)} d\beta(1.414) + \int_0^{\max(0,0.027)} d\beta(1.414)\right] \qquad (14)$$

Thus, PWL/100 = 1 - (0.0094 + 0.0094) = 0.9812, or PWL = 98.12 percent. This estimate is shown in Figure 4.

Equations 11 and 13 can now be used to develop tables that will simplify the estimating process. These tables are based on the fact that the PWL′ estimate for case 4 is constant for a given sample size n and given values of either $(U-\overline{X})/s$ and $(\overline{X}-L)/s$ for Equation 11 or $(U-\overline{X})/R$ and $(\overline{X}-L)/R$ for Equation 13. If it is designated that $Q_U = (U-\overline{X})/s$ and $Q_L = (\overline{X}-L)/s$ in Equation 11 and $Q_U = (U-\overline{X})/R$ and $Q_L = (\overline{X}-L)/R$ in Equation 13, then tables such as Table 6 (3, pp. 68-69), for the Equation 11 standard deviation method, and Table 7 (3, pp. 56-57), for the Equation 13 range method, can be developed.

Tables 6 and 7 are different from those that are currently used by state highway agencies that have the PWL type of acceptance plans. First, to avoid potential problems of interpretation, the tables are accurate to four decimal places (the tables commonly used by state highway agencies are accurate to two decimal places and may result in two different estimates from the same Q_U or Q_L value). Second, the only tables that have until now been readily available to state highway agencies are tables based on the range method. The biggest advantage of the range method is the ease of calculating R from the sample data. The advent of pocket calculators and computer programs developed to determine the contractor's payment is, however, increasing the attractiveness of the standard deviation method, which requires the calculation of s from the sample data. The two methods may give slightly different estimates of PWL′; the standard deviation estimate is the more accurate. For this reason, and because a smaller sample size can be used to achieve the same accuracy, it is recommended that highway agencies consider using the standard deviation method and Table 6.

Figure 4. Representation of the estimate of PWL′ using double specification limits when PWL is a function of $\overline{X}$ and $\overline{R}$ ($\overline{X}'$ and σ' unknown).

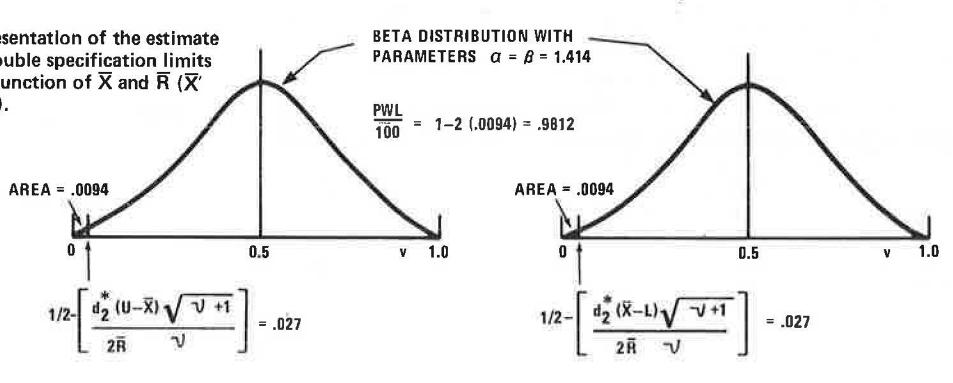


Table 6. Estimation of percentage within specification limits by standard deviation method.

	Negative Values of Q_U or Q_L						Positive Values of Q_U or Q_L				
PWL	n = 3	n = 4	n = 5	n = 6	n = 7	PWL	n = 3	n = 4	n = 5	n = 6	n = 7
50	0.0000	0.0000	0.0000	0.0000	0.0000	99	1.1510	1.4701	1.6719	1.8016	1.8893
45	0.1806	0.1500	0.1406	0.1364	0.1338	98	1.1476	1.4401	1.6018	1.6990	1.7615
40	0.3568	0.3000	0.2823	0.2740	0.2689	97	1.1439	1.4101	1.5428	1.6190	1.6662
39	0.3912	0.3300	0.3106	0.3018	0.2966	96	1.1402	1.3801	1.4898	1.5500	1.5868
38	0.4252	0.3600	0.3392	0.3295	0.3238	95	1.1367	1.3501	1.4408	1.4892	1.5184
37	0.4587	0.3900	0.3678	0.3577	0.3515	94	1.1330	1.3201	1.3946	1.4332	1.4562
36	0.4917	0.4200	0.3968	0.3859	0.3791	93	1.1263	1.2901	1.3510	1.3813	1.3990
35	0.5242	0.4500	0.4254	0.4140	0.4073	92	1.1170	1.2601	1.3091	1.3328	1.3465
34	0.5564	0.4800	0.4544	0.4426	0.4354	91	1.1087	1.2301	1.2683	1.2866	1.2966
33	0.5878	0.5101	0.4837	0.4712	0.4639	90	1.0977	1.2001	1.2293	1.2421	1.2494
32	0.6187	0.5401	0.5131	0.5002	0.4925	89	1.0864	1.1701	1.1911	1.2001	1.2045
31	0.6490	0.5701	0.5424	0.5292	0.5211	88	1.0732	1.1401	1.1538	1.1592	1.1615
30	0.6788	0.6001	0.5717	0.5586	0.5506	87	1.0596	1.1101	1.1174	1.1196	1.1202
29	0.7076	0.6301	0.6018	0.5880	0.5846	86	1.0446	1.0801	1.0819	1.0813	1.0798
28	0.7360	0.6601	0.6315	0.6178	0.6095	85	1.0286	1.0501	1.0469	1.0437	1.0413
27	0.7635	0.6901	0.6619	0.6480	0.6395	84	1.0118	1.0201	1.0125	1.0073	1.0032
26	0.7905	0.7201	0.6919	0.6782	0.6703	83	0.9940	0.9901	0.9782	0.9718	0.9673
25	0.8164	0.7501	0.7227	0.7093	0.7011	82	0.9748	0.9601	0.9453	0.9367	0.9315
24	0.8416	0.7801	0.7535	0.7403	0.7320	81	0.9555	0.9301	0.9123	0.9028	0.8966
23	0.8661	0.8101	0.7846	0.7717	0.7642	80	0.9342	0.9001	0.8798	0.8693	0.8626
22	0.8896	0.8401	0.8161	0.8040	0.7964	79	0.9122	0.8701	0.8479	0.8363	0.8290
21	0.9122	0.8701	0.8479	0.8363	0.8290	78	0.8896	0.8401	0.8161	0.8040	0.7964
20	0.9342	0.9001	0.8798	0.8693	0.8626	77	0.8661	0.8101	0.7846	0.7717	0.7642
19	0.9555	0.9301	0.9123	0.9028	0.8966	76	0.8416	0.7801	0.7535	0.7403	0.7320
18	0.9748	0.9601	0.9453	0.9367	0.9315	75	0.8164	0.7501	0.7227	0.7093	0.7011
17	0.9940	0.9901	0.9782	0.9718	0.9673	74	0.7905	0.7201	0.6919	0.6782	0.6703
16	1.0118	1.0201	1.0125	1.0073	1.0032	73	0.7635	0.6901	0.6619	0.6480	0.6395
15	1.0286	1.0501	1.0469	1.0437	1.0413	72	0.7360	0.6601	0.6315	0.6178	0.6095
14	1.0446	1.0801	1.0819	1.0813	1.0798	71	0.7076	0.6301	0.6018	0.5880	0.5846
13	1.0597	1.1101	1.1174	1.1196	1.1202	70	0.6788	0.6001	0.5717	0.5586	0.5506
12	1.0732	1.1401	1.1538	1.1592	1.1615	69	0.6490	0.5701	0.5424	0.5292	0.5211
11	1.0864	1.1701	1.1911	1.2001	1.2045	68	0.6187	0.5401	0.5131	0.5002	0.4925
10	1.0977	1.2001	1.2293	1.2421	1.2494	67	0.5878	0.5101	0.4837	0.4712	0.4639
9	1.1087	1.2301	1.2683	1.2866	1.2966	66	0.5564	0.4800	0.4544	0.4426	0.4354
8	1.1170	1.2601	1.3091	1.3328	1.3465	65	0.5242	0.4500	0.4254	0.4140	0.4073
7	1.1263	1.2901	1.3510	1.3813	1.3990	64	0.4917	0.4200	0.3968	0.3859	0.3791
6	1.1330	1.3201	1.3946	1.4332	1.4562	63	0.4587	0.3900	0.3678	0.3577	0.3515
5	1.1367	1.3501	1.4408	1.4892	1.5184	62	0.4252	0.3600	0.3392	0.3295	0.3238
4	1.1402	1.3801	1.4898	1.5500	1.5868	61	0.3912	0.3300	0.3106	0.3018	0.2966
3	1.1439	1.4101	1.5428	1.6190	1.6662	60	0.3568	0.3000	0.2823	0.2740	0.2689
2	1.1476	1.4401	1.6018	1.6990	1.7615	55	0.1806	0.1500	0.1406	0.1364	0.1338
1	1.1510	1.4701	1.6719	1.8016	1.8893	50	0.0000	0.0000	0.0000	0.0000	0.0000

Table 7. Estimation of percentage within specification limits by range method.

	Negative Values of Q_U or Q_L						Positive Values of Q_U or Q_L				
PWL	n = 3	n = 4	n = 5	n = 6	n = 7	PWL	n = 3	n = 4	n = 5	n = 6	n = 7
50	0.0000	0.0000	0.0000	0.0000	0.0000	99	0.5895	0.6574	0.6642	0.6611	0.6534
45	0.0970	0.0672	0.0573	0.0515	0.0477	98	0.5879	0.6440	0.6387	0.6264	0.6124
40	0.1911	0.1343	0.1149	0.1034	0.0957	97	0.5863	0.6307	0.6166	0.5983	0.5811
39	0.2093	0.1477	0.1265	0.1139	0.1055	96	0.5847	0.6173	0.5966	0.5744	0.5550
38	0.2274	0.1611	0.1382	0.1243	0.1152	95	0.5830	0.6039	0.5777	0.5530	0.5319
37	0.2451	0.1747	0.1497	0.1349	0.1252	94	0.5814	0.5905	0.5600	0.5330	0.5110
36	0.2625	0.1881	0.1614	0.1455	0.1351	93	0.5797	0.5771	0.5431	0.5143	0.4916
35	0.2798	0.2015	0.1732	0.1562	0.1450	92	0.5762	0.5638	0.5267	0.4968	0.4735
34	0.2965	0.2149	0.1835	0.1668	0.1549	91	0.5719	0.5504	0.5108	0.4800	0.4564
33	0.3131	0.2283	0.1968	0.1777	0.1649	90	0.5677	0.5370	0.4955	0.4640	0.4402
32	0.3293	0.2417	0.2086	0.1884	0.1752	89	0.5621	0.5236	0.4808	0.4485	0.4249
31	0.3450	0.2551	0.2206	0.1995	0.1854	88	0.5564	0.5101	0.4657	0.4337	0.4099
30	0.3604	0.2685	0.2325	0.2104	0.1957	87	0.5499	0.4967	0.4514	0.4191	0.3957
29	0.3754	0.2820	0.2446	0.2215	0.2061	86	0.5432	0.4833	0.4373	0.4050	0.3817
28	0.3901	0.2954	0.2567	0.2327	0.2166	85	0.5355	0.4699	0.4234	0.3913	0.3683
27	0.4041	0.3088	0.2689	0.2440	0.2273	84	0.5275	0.4565	0.4097	0.3778	0.3552
26	0.4179	0.3223	0.2811	0.2554	0.2380	83	0.5189	0.4431	0.3962	0.3647	0.3424
25	0.4311	0.3358	0.2935	0.2669	0.2489	82	0.5098	0.4297	0.3829	0.3517	0.3300
24	0.4439	0.3492	0.3059	0.2785	0.2599	81	0.5001	0.4162	0.3697	0.3391	0.3177
23	0.4560	0.3626	0.3184	0.2902	0.2712	80	0.4889	0.4028	0.3567	0.3266	0.3058
22	0.4679	0.3760	0.3311	0.3023	0.2825	79	0.4791	0.3894	0.3438	0.3144	0.2941
21	0.4791	0.3894	0.3438	0.3144	0.2941	78	0.4679	0.3760	0.3311	0.3023	0.2825
20	0.4899	0.4028	0.3567	0.3266	0.3058	77	0.4560	0.3626	0.3184	0.2902	0.2712
19	0.5001	0.4162	0.3697	0.3391	0.3177	76	0.4439	0.3492	0.3059	0.2785	0.2599
18	0.5098	0.4297	0.3829	0.3517	0.3300	75	0.4311	0.3358	0.2935	0.2669	0.2489
17	0.5189	0.4431	0.3962	0.3647	0.3424	74	0.4179	0.3223	0.2811	0.2554	0.2380
16	0.5275	0.4565	0.4097	0.3778	0.3552	73	0.4041	0.3088	0.2689	0.2440	0.2273
15	0.5355	0.4699	0.4234	0.3913	0.3683	72	0.3901	0.2954	0.2567	0.2327	0.2166
14	0.5432	0.4833	0.4373	0.4050	0.3817	71	0.3754	0.2820	0.2446	0.2215	0.2061
13	0.5499	0.4967	0.4514	0.4191	0.3957	70	0.3604	0.2685	0.2325	0.2104	0.1957
12	0.5564	0.5101	0.4657	0.4337	0.4099	69	0.3450	0.2551	0.2206	0.1995	0.1854
11	0.5621	0.5236	0.4808	0.4485	0.4249	68	0.3293	0.2417	0.2086	0.1884	0.1752
10	0.5677	0.5370	0.4955	0.4640	0.4402	67	0.3131	0.2283	0.1968	0.1777	0.1649
9	0.5719	0.5504	0.5108	0.4800	0.4564	66	0.2965	0.2149	0.1835	0.1668	0.1549
8	0.5762	0.5638	0.5267	0.4968	0.4735	65	0.2798	0.2015	0.1732	0.1562	0.1450
7	0.5797	0.5771	0.5431	0.5143	0.4916	64	0.2625	0.1881	0.1614	0.1455	0.1351
6	0.5814	0.5905	0.5600	0.5330	0.5110	63	0.2451	0.1747	0.1497	0.1349	0.1252
5	0.5830	0.6039	0.5777	0.5530	0.5319	62	0.2274	0.1611	0.1382	0.1243	0.1152
4	0.5847	0.6173	0.5966	0.5744	0.5550	61	0.2093	0.1477	0.1265	0.1139	0.1055
3	0.5863	0.6307	0.6166	0.5983	0.5811	60	0.1911	0.1343	0.1149	0.1034	0.0957
2	0.5879	0.6440	0.6387	0.6264	0.6124	55	0.0970	0.0672	0.0573	0.0515	0.0477
1	0.5895	0.6574	0.6642	0.6611	0.6534	50	0.0000	0.0000	0.0000	0.0000	0.0000

SUMMARY

The complete development of a PWL type of acceptance plan is founded on complex statistical theory. It is not necessary to understand the theory to use a PWL acceptance plan since estimation tables can easily be modified from Military Standard 414. However, if flexibility in adapting the standard to highway construction specifications is desired, a knowledge of the underlying theory is certainly helpful. Although one adaptation of Military Standard 414 plans—the range method—has gained a foothold in statistically based highway construction specifications, we believe that PWL plans are not being used to their fullest potential. It is hoped that the summary presented in this paper of the basic theory that underlies PWL acceptance plans will better equip highway agencies to develop acceptance plans specifically suited to their needs.

ACKNOWLEDGMENT

The contents of this paper reflect our views, and we are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Pennsylvania Department of Transportation or the Federal Highway Administration. This paper does not constitute a standard, specification, or regulation.

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Contractor Control of Asphalt Pavement Quality

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Warren Brothers Company builds asphalt pavements in seven states that use statistically based end-result specifications that require contractor control of quality. Company experiences with these seven different specifications are described, and control systems developed to comply with the specifications are explained. Problems and their solutions are discussed, and contractor costs and benefits are tallied. On balance, company experience with end-result specifications has been favorable. It is shown that end-result specifications can be workable for contractors, and improvements that would be beneficial to both contractors and agencies are suggested.

Over approximately the past 10 years, several state highway agencies have adopted end-result specifications for asphalt paving that encourage, if not require, contractor control of quality (1). All of these specifications are statistically oriented to some degree. There has been a high degree of interest in statistically oriented end-result specifications for about 20 years, but in spite of that interest implementation has been slow. One reason cited for the slow pace of implementation has been contractor resistance to change (1). This paper is concerned with the experiences and practices of one contractor—Warren Brothers Company, a division of Ashland Oil—with modern end-result specifications and quality control systems for asphalt paving.

HISTORICAL PERSPECTIVE

Contractor control of quality is not a new concept. In fact, early pioneers in bituminous paving such as Abbott, DeSmedt, and the Barber Asphalt Paving Company had their own quality control systems 100 years ago (2, 3). They had to have their own systems because nobody else knew how, but they had learned that control was necessary in order to duplicate successes.

Warren Brothers is no newcomer to quality control.

When Warren Brothers began building patented pavements in 1901, a quality control system was developed (4). This system was used successfully for over 40 years wherever Warren pavements were built.

Although contractors had control systems, paving specifications that required certain controls were in use before 1900 (2). By 1920, control by specification rather than by contractor was preferred (5).

Today, Warren Brothers Company operates 175 asphalt plants in 21 states and places pavements in 25 states. Annual production is about 13 000 000 Mg (14 000 000 tons) of asphalt concrete. Of these, 44 plants operate in seven states that use end-result specifications. A few plants located near state lines operate under both end-result and specification control. More than 10 years ago, the company began to participate in trials in these and other states. Overall company experience with modern end-result specifications is broad and varied, and it is from this multifaceted perspective that modern experiences are viewed.

MODERN END-RESULT SPECIFICATIONS

Acceptance Systems

Agencies in the seven states that use end-result specifications use seven different acceptance systems. The differences among the systems are significant and do not allow generalization. The requirements specified by these agencies are given below:

Requirement	Number of Agencies
Aggregate gradation	7
Number of sieves (typical surface mix)	
8	1
7	4
4	1
3	1
Asphalt content	7
Mix temperature	7
Marshall stability	4
Marshall flow	2
Air voids	1
Roadway density	5
Smoothness	4
Thickness	2

All seven agencies specify aggregate gradation, asphalt content, and mix temperature. One or more agencies specify up to six additional requirements. Agencies that do not specify density and smoothness have requirements for these items that are not included in their end-result specifications.

In addition to the number of requirements, the requirements themselves differ among agencies. The table above indicates that aggregate gradation is accepted on the basis of various numbers of sieves. More difference among grading requirements is illustrated below by a tabulation of requirements for one sieve:

Agency	Number of Tests per Lot	Tolerance for Average Result
1	5	±2.2
2	4	±4.3
3	2	±6.0
4	Unspecified	±3.0
5	5	±2.5
6	5	±4.7
7	4	±4.5

Similar differences are found for other sieves, asphalt contents, and requirements.

Acceptance is based on the lot—a specified unit of production—and a specified frequency of testing. Lot size can be one day's production (three cases), various amounts of material (three cases), or unspecified (one case). In some cases, provision is made to handle unusually large or small lots. The frequency of testing is shown in the table above where the indicated frequency is applicable to other requirements also. In some cases, mixture production lots and testing frequency are distinct from roadway lots and testing frequency.

Although it is not strictly a part of acceptance requirements, the job mix formula is an important consideration because it is the target that forms the basis of acceptance. In all seven cases, the contractor is required to submit a job mix formula that must then be approved by the agency. Approval involves duplicate testing in some cases and accepting the contractor's documentation in others.

Control Systems

One concept that has encouraged the adoption of end-result specifications is that, if end results are specified, control requirements can be eliminated entirely. This dream has not yet been realized. Many provisions of previous construction specifications have been retained and acceptance requirements simply added. This practice is correct because the previous specifications did not include explicit acceptance requirements. However, when new controls accompany the acceptance requirements, the net effect is an increase in control requirements.

Among the seven state agencies, the most elaborate new control system provides that the contractor furnish an agency-certified technician to perform all acceptance testing. Facilities and equipment for sampling and testing are specified. Acceptance tests are the basis of control. Altogether, test results for 10 mixture and pavement characteristics are reported on each sublot. All test results are recorded and plotted on control charts. Another agency has similar requirements for control but performs acceptance testing itself. Evidence of satisfactory control is, however, required.

Some controls are recommendations rather than requirements. One agency performs its own acceptance testing and recommends a control system for the contractor's consideration. Various random sampling plans are recommended for both acceptance and control, but none is specified. In general, it has appeared prudent for contractors to follow these recommendations as if they were requirements.

In some cases, no new control requirements are used. The contractor is free to do whatever he or she wants to ensure that the process is under control.

Complicating Factors

When end-result specifications are implemented, contractors are faced with a new acceptance system and must at least consider establishing a new control system. Frequently, there are additional considerations.

New acceptance systems are often accompanied by new requirements. For example, master ranges of aggregate gradation and asphalt content have been changed enough so that satisfactory mixtures that had been produced for many years would no longer be acceptable. Other examples of new requirements include Marshall stability and related criteria, density, and smoothness, all of which have been either new or applied in new ways with end-result specifications.

When considering a new control system, a contractor must also consider local aggregates. The control system at an asphalt plant to control aggregate gradation may range from almost nothing where aggregate producers have good control systems to a very intensive testing program where aggregate producers have poor control systems.

Local markets must also be considered. In addition to the local state agency, paving contractors also work for other government agencies, various authorities, private customers, and other contractors who purchase mixtures FOB. Some plants produce more than 20 job mixes and work with up to 10 aggregate sizes to comply with the various specifications. The contractor must make an end-result specification with new acceptance and control requirements compatible with the remainder of his or her operation or vice versa.

CONTRACTOR CONTROL SYSTEMS

Contractor control systems for end-result specifications begin with the specified controls. This includes many of the plant and construction controls from previous specifications and may include additional control tests. The next step is to establish whatever other controls may be needed to satisfy particular local conditions and still comply with the new acceptance requirements.

With Specified Controls

When additional control tests have been specified, test results for from 8 to 11 mixture and pavement characteristics are required on each sublot. Usually, there are four or five sublots per day. Test results are recorded and plotted on control charts as required.

This much work is a full-time job for one very good technician at one plant. Where required, the technician is agency certified. Because the technician's time is fully occupied with specified control testing, he or she does not perform other control work and is not expected to. The technician's job is to sample, test, and report as required—in other words, to produce the required evidence of control.

Evidence of control may be all that is needed to control the process. Minor adjustments of batch weights, cold-feed settings, burner temperature, and roller patterns, for example, can be accomplished on this basis before the process gets out of control.

Although this much evidence of control is certainly not too little, sometimes it is too late. In that case, additional personnel must be assigned to perform other control work to supplement but not duplicate the required control testing. Supplemental control testing concentrates on problem areas at a particular plant and should always occur at a point earlier in the process than the required control testing. Aggregates present the most frequent need for supplemental testing and may be tested at hot bins, cold feed, or the source as circumstances require.

Personnel requirements for supplemental control work vary, but someone must spend at least part time on it when it is needed. Sometimes supervisory personnel can perform the necessary work, but more often it has to be assigned to a technician who can concentrate on it. Rarely, however, does supplementary control work require a full-time technician when a plant already has a technician who works on required control tests.

Without Specified Controls

When contractor control testing and procedures are not specified, agency acceptance testing becomes the basis for control. There can be no other basis because it would be useless (even though possible) for a contractor to establish a control system that is incompatible with the acceptance system. In other words, if the control system indicates good control, the acceptance system should indicate an acceptable product.

Although control testing and procedures are not specified, an agency-certified technician usually is. Whether specified and certified or not, competent contractor personnel should be assigned to perform necessary control work. Full cooperation with the inspection personnel of the agency is perhaps the most essential aspect of the control technician's duties.

In addition to being the basis of control, agency acceptance testing can also serve as control testing. In these cases, control personnel do not have to do anything beyond monitoring test results and adjusting processes. However, more effective use of these personnel can be made, often depending on agency preferences. In some cases, inspection and control personnel work together on all aspects of the acceptance system. When sampling locations are selected by random numbers or some other device, both are present and both know that there is no bias. They obtain samples together and, if possible, each tests specimens of the same sample or in some way checks the other's testing. Test results are recorded, and control charts are plotted together. Discrepancies are investigated and corrected. In this way, both know with certainty that test results, whether good or bad, are correct. The duplication that characterizes this system may be wasteful, but it provides a very high degree of confidence for both parties and practically eliminates any possibility of dispute. Duplication can be advantageous: One of the two people performing the job—the contractor's technician—can find time for supplemental control work and thereby reduce or eliminate personnel requirements for this purpose.

In other cases, the agency prefers to work alone on acceptance, and the contractor's control is an entirely separate operation. Acceptance and control personnel work closely together, but control personnel are free to concentrate on the most troublesome areas. The control system is established to satisfy the demands of the local situation and may include duplication of the acceptance system, supplemental control tests, or some combination of the two. In practice, supplemental control tests have received the most attention because they allow concentrated effort where it is needed. Frequently, random sampling plans, standard test methods, control charts, and other necessary aspects of statistical quality control are not used because they do not help to solve the problem that the control testing is trying to overcome.

A situation in which agency acceptance testing was not useful in some way for control purposes has not been encountered. Some agency acceptance testing is more useful than others, and the contractor's control system must be established accordingly.

When no control system is specified, whatever system is established must be well documented. Sample locations must be pinpointed, and all test results—good and bad—must be recorded. Control charts can be useful and should be used when appropriate data are obtained. Control technicians do not find control charts to be particularly valuable because the technician knows the control situation when he or she obtains the test result; however, the charts are valuable to contractor supervisory personnel and agency personnel. All control records and charts and other control information, such as plant recordation, must be open and available to agency personnel at all times. The need for complete and open documentation of control cannot be overemphasized because these documents form the basis for appeal when acceptance testing indicates an inferior product. Erroneous acceptance testing has been discovered and corrected in this way. This feature of control documentation is to the contractor's advantage because it has always been used to correct indications of inferior products and never to correct indications of acceptable products.

PROBLEM AREAS

A great variety of problems have been encountered through the years with the several systems. Ultimately, the major problems revolve around acceptance testing identifying inferior products.

Difficult Requirements

Compliance with certain acceptance requirements has been difficult, if not impossible, in some cases. These experiences suggest that the acceptance requirements may not be realistic. For example, a table given previously reveals different tolerances for one mixture characteristic. Even when allowance is made for the number of tests, it is difficult to avoid the conclusion that all tolerances cannot be right and some may be unrealistic. An unrealistic tolerance could be either too small or too large. Too small results in frequent noncompliance and is the difficult requirement. Too large is not difficult but results in acceptance of inferior products, an unfavorable situation for both agency and contractor.

Most difficult requirements are in some way new requirements that had to be established based at least partly on engineering judgment. Aggregate gradation, which the table on tolerances illustrates, is a time-honored, traditional basis for control and acceptance, but the use of random sampling and statistical procedures is new. Thus, tolerances for this and for other traditional characteristics as well required judgment. Experience suggests that many of these tolerances may be realistic for major paving operations in which continuous operation is possible but unrealistic for bridge approaches, intersections, and other irregular areas that are a part of nearly all paving contracts and require stop-and-go, low-production operation. Experience also suggests that tolerances that appear to be realistic for surfaces are unrealistic for bases, but one set of tolerances is applicable to both.

New, difficult requirements have also been encountered with respect to pavement smoothness, thickness, and density. In the past, these items were controlled mostly by method requirements rather than result. Experience shows that full compliance with these new requirements has not been possible in some cases when the old methods were used and in other cases no matter what methods were used. A majority of paving contracts involve leveling or base courses or both, but the new acceptance requirements appear to be reasonably applicable only to surface courses and then only if the contract provides enough leveling so that a smooth, dense surface can be built.

Feedback

It has already been noted that acceptance requirements are the basis for control and that acceptance testing can be used for control. Either way, prompt reporting of acceptance test results to the contractor is essential. Otherwise, the contractor does not know where he or she stands no matter what quality control system is used because acceptance tests are the bottom line. Delay appears to serve no useful purpose, and it does prolong undesirable situations that could be corrected. Prompt and timely reporting of acceptance test results is the practice in many cases. No overwhelming reason is known for not practicing it in all cases.

Number of Requirements

Most agencies use approximately 10 acceptance requirements, and some require an equal number of controls. If the probability of acceptance of one requirement is 0.99, most statisticians would agree that the process is under very good control with respect to that requirement. When there are 10 such requirements, the probability that their combination is acceptable is 0.99^{10} or 0.90. If the requirements are not mutually exclusive, which is usually the case with paving requirements, the probability is less than that. Even though there is ample evidence that actual processes are under good control, the number of requirements makes full compliance with all requirements all of the time unlikely. Yet, a process under good control should be able to comply.

Reproducibility

Two or more laboratories are often involved in mix design, control, and acceptance. The reproducibility of the results of most of this testing is judged to be poor. Discrepancies between laboratories in excess of specified tolerances is expected. Mix designs that cannot be produced have been required, and mix designs that another laboratory could not duplicate and therefore accept when produced have been required.

When control testing is specified, the problem is not reproducibility because the laboratories test different materials. However, some sort of agreement between laboratories is required and is often unattainable within specified tolerances. When control testing is not specified, the problem does not exist even though laboratories do not agree because the objective of control testing is control rather than agreement.

Judgment

In theory, statistically based end-result specifications require no judgment in application because all decisions were made when the specifications were written. In practice, experience shows that judgment is needed. Because of the variety of circumstances encountered in pavement construction, it is unlikely that all situations can be anticipated. Decisions made in the field are necessary and often advantageous to all parties.

EVALUATION OF CONTROL AND ACCEPTANCE SYSTEMS

Contractor Costs

In every case in which responsibility for quality control has passed from the agency to the contractor, there has been an increase in contractor costs. These costs vary with circumstances and stem from several sources. Whatever they add up to, these costs must be included in bids.

Qualified personnel must be made available. In a few cases, qualified quality control personnel were already present and only needed to assume new duties. The work that they had been doing still needed to be done and had to be assigned to others but with a minimum of new hiring. In most cases, additional quality control personnel must be hired. One technician per plant is not always required. Multiplant operations can be handled by a team of technicians who concentrate their efforts where needed.

Training of personnel is an additional cost. Because an agency-certified technician is required in most cases, training is not optional. Where agency certification is required, more training than necessary appears to be desirable even though expensive. Supervisors and plant foremen have been trained so that the required presence of a certified technician is ensured. Additional training by the contractor usually follows depending on the experience and background of the personnel.

Laboratory facilities and equipment represent another cost. In some cases, this has amounted to practically nothing because suitable laboratories were already present. Minor repair and replacement costs have been incurred. In other cases, new equipment and buildings have been necessary. Although these costs are high, they are depreciated over several years, which results in substantial but not excessive annual costs.

The final cost item is the penalties that are part of every statistically based end-result specification. Although alarming penalties have occasionally been assessed, generally penalties have not been excessive. Where penalties have been large, the cause has been found and corrected. More often than not, the cause was the specification. Today, penalties amount to a small fraction of 1 percent of contract prices, which is regarded as about as good as possible. Bids must bear the cost of penalties, but a separate item for penalties is not included in cost estimates.

There are also hidden costs of penalties. When a penalty is assessed, it would be folly not to investigate it. This may involve supervisors, plant and street crews, and estimators in addition to control personnel. Although such an investigation may pay significant dividends either immediately or in the future, it does cost time and effort.

The most significant cost of penalties is poor psychology. One supervisor reported that he was not dealing with an end-result system but a penalty system. Another stated that penalties were very rare but too often too close for comfort. Both were working to avoid penalties and could do a better job working toward incentives. Penalties, even though only occasional and small, must be explained by quality control personnel. With an incentive system, the same personnel would occasionally be praised and would not have to explain anything.

Contractor Benefits

Although there are costs associated with contractor control of quality, there are also benefits that at least partly offset the costs.

All end-result specifications require contractors to submit mix designs. Contractor mix designs are often more economical and easier to produce than agency mix designs because the contractor's knowledge of materials is different from the agency's knowledge of the same materials. If the same mixture can be used by other customers, significant cost reductions are possible.

Control personnel are not fully occupied all of the time on control of agency jobs. Their free time can be devoted to mix design, concentrated effort on problem areas, helping other customers with quality control, and a variety of related work. Experience shows that control personnel can always be used effectively even though required agency work may occupy less than half of their time.

Other personnel, such as plant and laydown crews, can be used more effectively to control quality. They can make minor, previously prohibited adjustments. Any adjustment must be reported to control personnel, but it can be made when it is needed. Timely, minor adjustments can eliminate problems before they become serious. When personnel can make such minor adjustments, they develop an improved attitude toward quality.

In most cases, cooperation between contractor and agency has improved. Lines of authority and responsibility are more distinct and logical. Adversary relationships that sometimes existed have disappeared. A side benefit is improved relations with other customers who have been ready and willing to accept contractor control even though their specifications do not provide for it.

Most benefits of contractor control are intangibles that are not readily reduced to bookkeeping entries. Whether or not the costs outweigh the benefits cannot be determined. However, even if costs exceed benefits, contractor control appears to be worth the cost in most cases.

FUTURE IMPLEMENTATION

On balance, company experience with modern end-result specifications and contractor control of quality has been favorable. Major difficulties have been corrected either internally or through agency cooperation. Accordingly, further implementation can be expected in the future.

Future end-result specifications can be improved if quality can be ensured by more realistic requirements and procedures. The areas to be considered include tolerances, number of requirements, reproducibility, feedback, and penalties. Of these, realistic tolerances and fewer requirements will probably be the most difficult to achieve. Penalties can be replaced by incentives. Reproducibility and feedback problems are not present in some existing systems and could probably be eliminated from all.

Even more improvement could be expected if, instead of one end-result specification per agency, there were just one end-result specification. A standard end-result specification used by all would be easier for everyone to understand. Contractors, who have been accused of resisting the adoption of end-result specifications, would resist less and perhaps not at all if they were faced with a specification that contained realistic, understandable requirements. Agencies could communicate with each other better and learn more from each other's experiences. The machinery for developing such a standard already exists in the American Society for Testing and Materials. That machinery can be used to everyone's benefit.

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Equitable Graduated Pay Schedules: An Economic Approach

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An approach for establishing graduated pay schedules that are realistic, equitable, and legally defensible is presented. The method consists of determining the present worth of the extra expense anticipated in the future as a result of work of deficient quality. An appropriate pay schedule is developed on the premise that it would be justifiable to withhold this amount from the contract price. The method is applicable in the case of construction items for which data are available that relate quality to performance. An example is given in which concrete pavement is evaluated in terms of compressive strength.

In recent years, engineers have begun to recognize that most design parameters are variables and that it is not uncommon (or necessarily undesirable) for a small percentage of test results to fall below some prescribed design value. Even when a greater number of tests fall below this value, experience has shown that the net result may simply be a loss of serviceability. Because of the impracticality of removing and replacing an item that is only slightly deficient, engineers have begun to rely on statistically oriented end-result specifications that use graduated pay schedules to award payment in proportion to the quality received.

Of prime importance in the development of specifications of this type is the establishment of realistic and equitable pay schedules. The approach presented in this paper is an extension of methods suggested in other recent writings (1, 2). In principle, it is as follows: When tests indicate that a construction item is of substandard quality, withhold payment that, when deposited at compound interest, will provide sufficient funds in the future to restore the item to its intended (design) condition. In other words, the amount to be withheld is the present worth of the extra expense anticipated in the future as a result of deficient workmanship.

EXAMPLE

Suppose it is desired to develop a pay schedule for concrete pavement based on compressive strength. Assuming a design strength of 27.59 MPa (4000 lbf/in^2), a coefficient of variation (CV) of 15, and an acceptable quality level (AQL) of 10 percent below design strength, the average strength of AQL concrete will be 34.14 MPa (4950 lbf/in^2). Furthermore, based on historical data or engineering judgment or a combination of both, suppose it is decided that the worst quality to be accepted even at reduced payment (the rejectable quality level or RQL) will have 50 percent of the material below design strength. Concrete of this quality will have an average strength of 27.59 MPa (4000 lbf/in^2).

Before the expected loss in allowable load repetitions for a shift in quality from AQL to RQL [defined by a shift in compressive strength from 34.14 to 27.59 MPa (4950 to 4000 lbf/in^2)] can be calculated, it is first necessary to determine the corresponding loss in flexural strength (modulus of rupture). Data presented by Urquhart (3) can be used to estimate the following relation for concrete that has a compressive strength between 20.69 and 48.28 MPa (3000 and 7000 lbf/in^2):

$$y = 1.97 + 0.0709x \qquad (1)$$

where

y = flexural strength (modulus of rupture) (MPa) and
x = compressive strength (MPa).

Then, since the working stress is defined as 75 percent of the modulus of rupture, the following values can be calculated (1 MPa = 145 lbf/in^2):

Quality Level	Compressive Strength (MPa)	Flexural Strength (MPa)	Working Stress (MPa)
AQL	34.14	4.39	3.29
RQL	27.59	3.92	2.94

To determine the reduction in allowable load applications, the American Association of State Highway Officials (AASHO) nomograph for rigid pavements with a terminal serviceability index (p_t) of 2.5 (4), shown in Figure 1, will be used. Assuming the pavement was designed to handle 1000 daily 80-kN (18 000-lb) equivalent load applications and that the modulus of subgrade reaction k is 1.21 MPa (175 lbf/in^2), the solid line in this figure indicates that this pavement should be 24.1 cm (9.5 in) thick. However, if it is built with this thickness but because of improper materials or workmanship happens to be of RQL quality instead of AQL quality, the dashed line indicates that it will be capable of sustaining only about 700 daily load applications instead of 1000.

Next, this must be converted to time to failure (i.e., time at which an overlay is required). If the traffic volume were constant, the time to failure would be directly proportional to the number of allowable load applications, and the RQL pavement in this case would be expected to last about 70 percent as long as the AQL pavement. However, if there were a tendency for the traffic count to increase over a period of years, fewer of the allowable load applications would occur during the early part of the service life of the pavement and, as a result, it would not reach failure quite as quickly as if the traffic count were constant with time. The following expression for predicted service life can be derived:

$$n = \ln\{1 + (d/D)\,[(1 + R)^N - 1]\}/\ln(1 + R) \qquad (2)$$

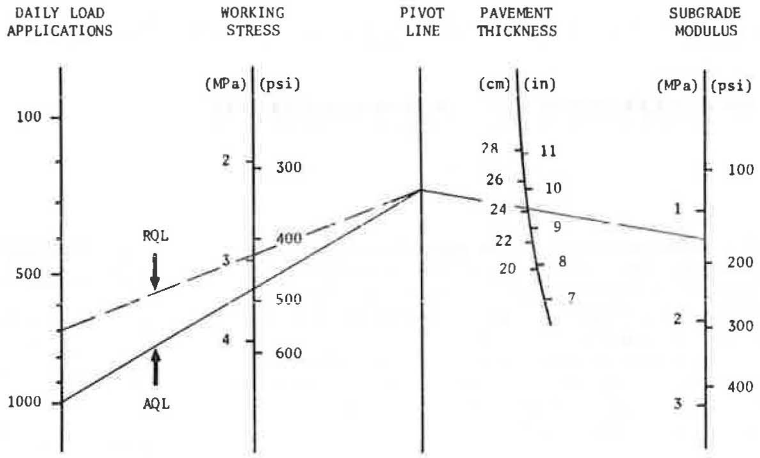
where

n = predicted service life (years);
d = reduced number of daily 80-kN (18 000-lb) load applications determined from AASHO nomograph;
D = design daily 80-kN load applications;
R = yearly traffic count increase expressed as a decimal (although it is not permissible to use R = 0 in this expression, it can be demonstrated that, as $R \to 0$, $n \to dN/D$); and
N = design service life (years).

Although the AASHO method is developed for a 20-year analysis period, suppose local experience has shown that pavements designed by this procedure will last an average of 25 years when properly constructed. Assuming a traffic increase of 2 percent/year (R = 0.02), the following calculation can be made:

$$n = \ln\{1 + (700/1000)\,[(1 + 0.02)^{25} - 1]\}/\ln(1 + 0.02) = 18.7 \qquad (3)$$

Figure 1. AASHO design chart for rigid pavements.



Thus, with an increase in traffic of 2 percent/year, a pavement that has been determined to be capable of sustaining about 70 percent as many load applications by use of the AASHO nomograph is seen to have a service life about 18.7/25 = 75 percent as long as would normally be expected.

In this example, the RQL pavement will require an overlay after 19 years—6 years sooner than the AQL pavement. To determine the present worth of the extra cost of this premature failure, basic engineering-economics formulas (5) are used along with the following data ($1\ \mathrm{m}^2 = 1.2\ \mathrm{yd}^2$; 1 cm = 0.39 in):

Item	Amount
In-place cost of concrete	$\$21.52/\mathrm{m}^2$
In-place cost of overlay	$\$0.54/\mathrm{cm}/\mathrm{m}^2$
Interest rate	5 percent
Inflation rate	4 percent

In the calculations, the depreciation of an overlay is assumed to be proportional to the length of time it has been in service. For example, if the expected life of an overlay is 10 years, after 7 years its salvage value is considered to be 30 percent of the cost of installing a new overlay at that time.

For this example, it will be assumed that the overlay on the RQL pavement will have to be about 7.6 cm (3 in) thick (because of such factors as cracking and faulting) and that it will have an expected life of 10 years. This overlay will be required 19 years in the future, and at that time its cost will be $7.62 \times \$0.54 \times (1 + 0.04)^{19} = \$8.67/\mathrm{m}^2$ ($\$7.27/\mathrm{yd}^2$). If the interest rate of 5 percent/year, compounded monthly, is used, the value of this money at the 25th year (6 years later) would be $\$8.67 \times [1 + (0.05/12)]^{12\times 6} = \$11.70/\mathrm{m}^2$ ($\$9.81/\mathrm{yd}^2$). At that time, the overlay will have a 40 percent salvage value, which is $0.4 \times 7.6 \times \$0.54 \times (1 + 0.04)^{25} = \$4.38/\mathrm{m}^2$ ($\$3.68/\mathrm{yd}^2$). The extra cost incurred as a result of deficient quality will be the difference between these last two values, or $\$11.70 - \$4.38 = \$7.32/\mathrm{m}^2$ ($\$6.13/\mathrm{yd}^2$). To convert this back to present worth, the following expression is used: $\$7.32/[1 + (0.05/12)]^{12\times 25} = \$2.10/\mathrm{m}^2$ ($\$1.76/\mathrm{yd}^2$).

Since this is the amount of money that must be invested at compound interest at the time of construction to pay for the future cost of restoring the pavement to its intended (design) condition, it would seem equitable to withhold this amount from the contract price. However, before this result can be used to calculate an appropriate pay schedule, it is necessary to consider the following factors not included in the economic analysis:

1. There will be administrative costs involved in preparing for the premature repair of poor-quality pavements.
2. There will be a cost to the motoring public for earlier and more frequent disruption of traffic to make the necessary repairs.
3. A section of poor-quality pavement will almost certainly make it necessary to overlay a larger section of pavement. For example, if one lane fails, all adjacent lanes will receive an overlay. Similarly, practical considerations will often make it necessary to overlay an entire length of pavement even though only a portion of it has failed.
4. Premature failures, which necessitate additional unanticipated rehabilitation work, could severely restrict the priority-setting capabilities of a highway agency.

Attempts to include item 1, administrative costs, as some fixed percentage of construction costs show this to have little effect on the pay schedule that is ultimately developed. Item 2, the costs associated with inconveniences and delays to the motoring public, is extremely difficult to quantify but does suggest that some increase in expected costs is warranted. Item 3 can be approximately quantified and is seen to have a very significant effect. If a failed section in one lane causes just one adjacent lane to be overlaid, this immediately doubles the cost while providing very little additional benefit. Furthermore, if a failed section (or sections) causes a lengthier section to be overlaid, this cost might easily be doubled again, resulting in a fourfold increase. Finally, if many early failures were to occur, item 4 indicates that some very serious scheduling difficulties might arise. Since fixed appropriations are allotted for maintenance work, the occurrence of several pavement failures might lead to substantial delays in making the necessary repairs. If increased appropriations were not forthcoming, these delays could become prolonged, which would further accelerate the deterioration, cause driving conditions to become more hazardous, and make subsequent repairs even more costly.

Because of the potentially devastating effect of the occurrence of many substandard construction projects, plus the fact that it should be the highway agency's goal to build quality pavements that do not fail prematurely, it is felt that the reduced pay factor for RQL (truly inferior) construction should be set low enough to ensure that the buyer (i.e., the taxpayer) gets his money's worth and that sufficient incentive is provided for the contractor to produce quality workmanship. Since item 3 by itself indicates that the estimated costs of future repairs should be multiplied by a factor of 2 or more, it is felt that a multiplication factor of at least 3 should be used to account for all unquantified items. The present worth of the cost to repair RQL quality pavement is then estimated to be 3 × \$2.10 = \$6.30/m^2 (\$5.28/yd^2) and the appropriate percentage payment, based on the bid price of \$21.52/m^2 (\$18.00/yd^2), is (\$21.52 - \$6.30)/\$21.52 = 70.7 percent, which, for practical purposes, is rounded off to 70 percent.

The next step is to develop an acceptance procedure and a graduated pay schedule that, on the average, will award 70 percent payment for RQL-quality concrete. In an earlier paper (6), it was demonstrated that the average pay factor actually received for RQL-quality concrete will be substantially higher than the minimum value in the pay schedule. This is true because many RQL lots will receive pay factors higher than the minimum value and these, in turn, bring the average up. More recent work by the author has shown that a minimum pay factor of 50 percent will produce an average pay factor between 70 and 80 percent for truly rejectable concrete. Based on this, a minimum pay factor of 50 percent is judged to be appropriate.

Once the minimum pay factor for RQL-quality construction has been established, it remains to develop a series of graduated pay factors that correspond to quality levels between the AQL and the RQL. If one recognizes that the consequences of deficient concrete become much greater as the deficiency increases, it would seem reasonable to graduate the pay schedule in a nonlinear fashion so that concrete that is only slightly below the AQL would receive nearly full payment. One possible pay schedule that uses five steps and an RQL pay factor of 50 percent would be as follows:

Quality	Pay Factor (%)
AQL	100
	95
	85
	70
RQL	50

In addition to this, most agencies would want to reserve the option to require removal and replacement of any material found to be at or below the RQL.

It is not the purpose of this paper to discuss the development of the acceptance procedure by which the actual quality of a product is estimated. This information may be obtained from many sources (7, 8, 9). When this is completed, it would be wise to use computer simulation (10) or other means to confirm that the expected pay factors for various levels of quality are reasonable and equitable.

SUMMARY

The intent of this paper is to present by example a rational and logical method for determining the value of an item of substandard quality to provide solid justification for the use of statistically oriented end-result specifications with graduated pay schedules. It is suggested that the present worth of the additional future cost anticipated as a result of construction of deficient quality is a sound basis for the determination of an equitable pay reduction. It is recognized that this method is appropriate only for items for which there are data that relate quality to performance (or expected life), but it is believed that there are a sufficient number of such cases to warrant serious consideration of this approach.

The example presented concerns the development of a pay schedule for concrete pavement based on compressive strength. By using the same AASHO nomograph, it would also be possible to develop a pay schedule based on pavement thickness and, in fact, these two parameters of quality—strength and thickness—could be used jointly. Similarly, a pay schedule based on thickness could be developed for flexible pavements.

It is believed that the information needed to apply this procedure is readily available within most state highway agencies although it is recognized that the choice of specific interest and inflation rates requires the assumption that these rates can be accurately projected some distance into the future. The values used in the example were chosen for purposes of illustration and, as would be expected, slightly different input values will produce slightly different results. Users of this method are cautioned that care should be taken to determine appropriate input values for the agency for whom the specification is being developed.

ACKNOWLEDGMENT

The findings and opinions presented in this paper are mine and do not necessarily reflect the views of the New Jersey Department of Transportation.

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Construction Industry Response to a Statistically Based Bituminous Concrete Specification in New Jersey

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The evolution of a statistically based specification for bituminous mix in New Jersey is reviewed. How five producers of asphalt mix dealt with the specification and their various attitudes and approaches toward design and quality control are discussed. An overview is presented of studies by the New Jersey Department of Transportation of projects run under the specification. Particular problems with the specification encountered by both the producer and the state are cited. Revisions to the specification that were used in an effort to correct the various problems are outlined. Finally, a critique is given of the specification as it evolved and as it stands today.

Before 1968, virtually all bituminous mix design and testing in New Jersey was performed by state highway department personnel. The 1961 Standard Specification for Road and Bridge Construction was still the basic specification in use. The salient provision of this specification related to bituminous concrete (specifications cited in this paper refer to U.S. customary units of measurement; therefore, no SI equivalents are given):

> Formula for Job Mix. The composition limits for every mixture as prescribed in [Table 1] are extreme ranges that must not be exceeded.
>
> The Laboratory will establish a job mix formula for each mixture to be supplied for the Project. The job mix formula shall be in effect until modified by the Laboratory. The job mix formula for each mixture shall establish a single definite percentage of mineral aggregate to be weighed from each bin, a single definite percentage of bituminous material to be added to the aggregate, the percentage or amount of any other ingredient that may be required, and the temperature at which the mixture is to leave the plant, all within the ranges of the specifications for the specific type of mixture. Should a change in sources of materials be made, a new job mix formula may be established before the mixture containing the new materials is produced.

After the job mix formula was established for a mixture as prescribed in Table 1, all mixtures of that type furnished for the project were to conform within the following tolerances:

Material	Tolerance (%)
Coarse aggregate, bottom course (total retained on no. 10 sieve)	±5
Coarse aggregate, top course (total retained on no. 10 sieve)	±4
Bitumen content for type SA top course	±0.5

Essentially, the producer was required to manufacture a mix that conformed to the master range of the gradation table and an asphalt content within a specified tolerance of design. With the exception of the bituminous stabilized base course, no Marshall testing was specified for any mix. All acceptance testing (and most quality control testing) was performed by state highway personnel.

In 1967 several factors were operating to move the New Jersey Department of Transportation (DOT) to revise their bituminous concrete specifications. From the viewpoint of industry, there was concern about the specifications for raw aggregate. It was felt that the fine aggregate requirement not only was difficult to meet (thus limiting sources of supply) but also contributed to unstable mixes. The coarse aggregates that were specified on the basis of percentage retained through sieves with round openings were also often difficult to obtain. In addition, the state's northern producers, who were involved with several different agencies (e.g., New York State, New York City, port authority), wanted to obtain a more standardized specification.

From the viewpoint of the state DOT, there was growing concern about the legal position in relation to projects in which material was found to be defective. Since personnel of the department had been responsible for both the design and quality control of the mixes, the department could not be considered totally free of responsibility should the material not meet specifications. There was also a desire to adopt a more standardized specification consistent with the national trend at that time.

It was in this atmosphere that the first "Addenda A" (revision to the standard specification for bituminous concrete) was conceived. The department felt that the specification should contain the following basic provisions:

1. A shift of responsibility for design and quality control of mixes from the state DOT to the producer,
2. Partial end-result specification in that there would be no gradation requirement for raw aggregates or hot bins at the plant so long as the producer could meet the finished mix parameters,
3. A more standardized specification basically molded after ASTM D 1663-67,
4. A reduced payment schedule for material deemed not in conformance with minimum performance requirements, and
5. Statistically based sampling and testing concepts that would provide some solid basis for item 4 above.

The producers were in favor of the first three items but not the last two. In January of 1968, the department published an interim revision that incorporated the first three concepts. This interim specification, termed "pink Addenda A," could be used as an alternate during this period by any producer who opted to do so.

The initial reaction of most producers to pink Addenda A was favorable. Although some added costs were incurred for mix design and quality control services, most felt that this was more than offset by the use of other, less costly raw materials and the ability to design and control their own mixes. The first adverse reaction on the part of the producer did not come until after the publishing of the November 1968 revision of Addenda A, which was the first statistically based specification (incorporating the last two provisions in the list above). From this time on, the Addenda A specification was

Table 1. Requirements for hot-mixed bituminous concrete and sheet asphalt from 1961 specifications.

Total Aggregate		Percentage by Weight						
Passing	Retained On	Mix 1	Mix 2	Mix 3	Mix 4	Mix 5	Mix 6	Mix 7
Screen, in	Screen, in							
1.5	1	0-35	0-25					
1	0.5	25-70	20-45	8-25	0-10	0-5		
0.5	0.75	0-20	10-25	20-45	12-40	20-35	0-10	
	Sieve							
0.75	No. 10	0-15	5-15	5-25	8-30	15-30	8-25	0-5
Sieve								
No. 10	No. 30	1-11	2-14	2-14	2-17	8-22	3-20	4-25
No. 30	No. 50	2-15	5-18	5-18	4-24	4-15	8-30	10-35
No. 50	No. 80	2-14	4-18	4-18	6-22	3-15	10-28	12-33
No. 200		0-5	4-8	4-8	4-8	4-8	4-10	10-15
Total retained on no. 10 sieve		55-85	45-65	45-65	30-60	40-55	15-30	0-5
Bitumen content (solubility in benzol)		4-6	5-7	5-8	5.5-9	5-8	8-11	9-11.5

Notes: All screens 0.75 in and larger are round openings.
Aggregate to be used for the following pavement courses: mix 1—all bottom courses; mix 2—CA-BC-1, CA-BC-2, top; mix 3—MA-BC-1, MA-BC-2, top; mix 4—FA-BC-1, FA-BC-2, top; mix 5—SM-1, SM-2, top; mix 6—SP-1, SP-2, top; and mix 7—SA, top.

viewed with disdain and skepticism by many producers.

The pertinent provision of the November 1968 Addenda A can be found in Figure 1. Essentially, it calls for a lot of five samples to be taken for each 1500 tons of finished mix. A random number table was used to select the precise ton that was to be sampled in each sublot of 300 tons. Five quality parameters were selected for evaluating samples of mixtures taken at the plant. Three parameters were concerned with gradation, one with asphalt content, and the last with Marshall stability. The sixth parameter involved air voids, which were determined by using core samples taken from the finished pavement. The producer had to have a quality control technician present during all productions for state projects.

Tables of tolerances for gradation and asphalt content were included based on statistical analysis of central laboratory extraction data (primarily of road cores dating back to 1961). The tolerances in the first table were based on two standard deviations. This was applicable to single samples and was intended to control the range between individual samples in the lot. The tolerances in the second table were based on one standard deviation and applicable to the lot average.

Under this specification, there were two sets of requirements for the Marshall properties: First, a minimum stability was required for mix designs; second, a lower "control" standard was specified for a set of three specimens molded at the producer's laboratory from a material used for one of the five composition samples in a lot. For air voids, a wider range was again used for control than for design. In this case the control air-void requirement was applicable to individual cores taken for approximately every 2000 yd^2 of pavement.

In line with the department's concern about enforcement of the new specifications, provisions for payment reduction were incorporated for the five parameters to encourage producers to make every effort to comply. The November 1968 revision was a substantial change, then, from the standard 1961 specifications. Even though the rate of sampling and the tolerances had remained about the same, the shifting of responsibility for design and quality control, the increase in the number of parameters, and the inclusion of Marshall property requirements made the transition somewhat involved and difficult.

In 1968, very few producers had quality control personnel. With this in mind, the New Jersey DOT and the New Jersey Asphalt Paving Association jointly contracted with a consultant to give a 2-week course on mix design and quality control of asphalt pavement. This program was first held in February 1968 and was attended equally by both department personnel and employees of producers. Many other producers hired outside consultants to do their mix designs and quality control work. Very little if any in-house design or quality control of asphalt mixes was carried on by the producers before the new specifications were issued. Virtually all endeavors at a statistically based quality control program were a direct result of the requirements of the new specifications. All parties concerned were novices at this time, and much of the work was done by the trial-and-error method.

The response of five producers to the new specifications is detailed below. They are intended to be a fairly representative cross section of New Jersey producers.

PRODUCER A

Located in north-central New Jersey, producer A owns four asphalt plants in two locations and one quarry. Before 1968, there was one full-time quality control employee. His primary responsibility was the quarry and, although he performed some limited control on the asphalt mixes, the majority of this activity was taken care of by the state inspector. After 1968, one additional quality control person was hired.

Mix designs formulated by the quality control personnel represented basically the same mixes as those used under the old specifications. Because of a high rate of production and therefore of sampling, the technician had little time to do anything except acceptance testing. Raw aggregate or hot-bin gradation data were not normally collected—only the information required by the specification. The only additional test run was for "stone content," which consists of soaking the hot mix in gasoline, burning off the asphalt cement, and running a gradation on the stone retained above the no. 8 sieve. This test was used with some regularity as a quick check on the mix gradation. Only one specification parameter (amount passing the no. 8 sieve) could be checked by means of this test. No graph or chart of data was used. Most control was based on single extraction samples taken within a lot. In many cases, an entire lot of material—i.e., 1360 Mg (1500 tons)—would be produced in 1 d. Since the New Jersey DOT extraction test procedures were more involved than normal (requiring that the gradation on the aggregate after extraction be a washed gradation, which usually adds approximately 1 h to the normal test time), a competent technician could not normally be expected to run more than five extractions in an 8-h day. This meant that there was no time for additional quality control testing and therefore control judgments had to be based on acceptance samples.

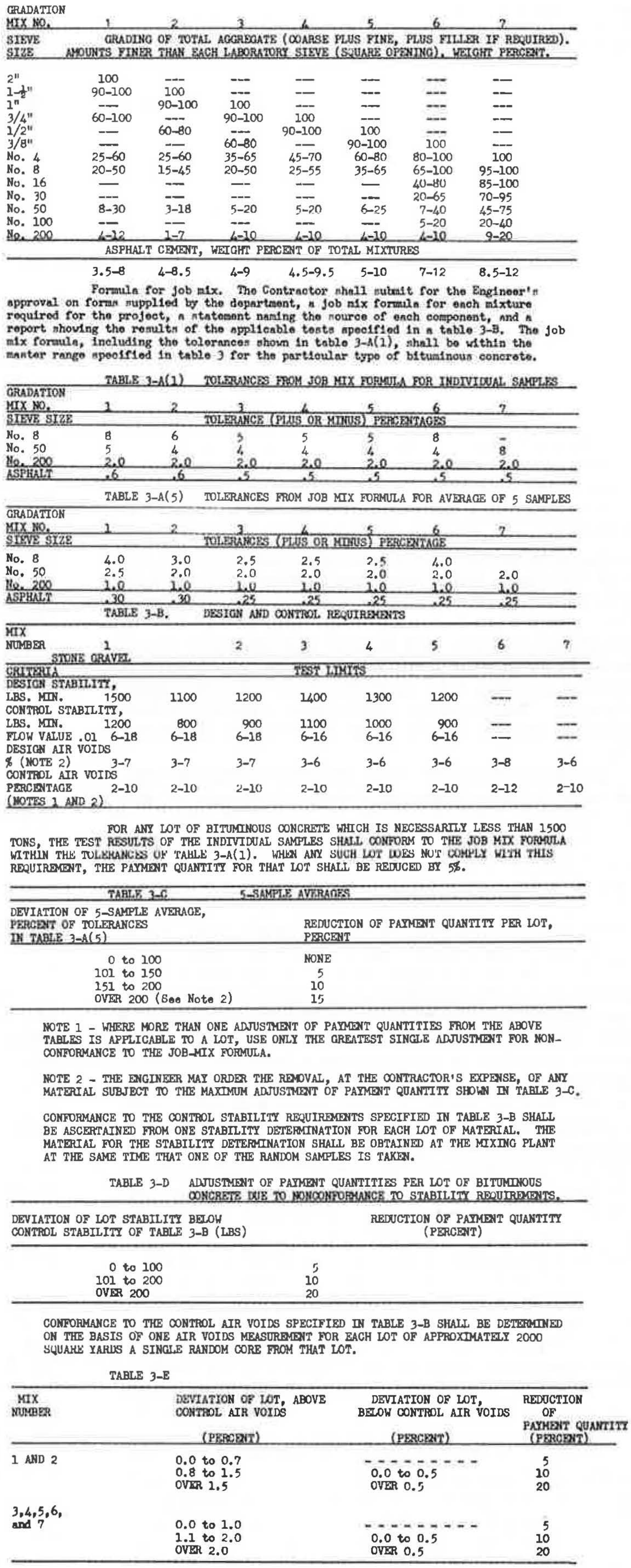


Figure 1. Provision of November 1968 Addenda A revision to specifications for bituminous concrete.

GRADATION MIX NO.	1	2	3	4	5	6	7
SIEVE SIZE	GRADING OF TOTAL AGGREGATE (COARSE PLUS FINE, PLUS FILLER IF REQUIRED). AMOUNTS FINER THAN EACH LABORATORY SIEVE (SQUARE OPENING), WEIGHT PERCENT.						
2"	100	---	---	---	---	---	---
1-½"	90-100	100	---	---	---	---	---
1"	---	90-100	100	---	---	---	---
3/4"	60-100	---	90-100	100	---	---	---
1/2"	---	60-80	---	90-100	100	---	---
3/8"	---	---	60-80	---	90-100	100	---
No. 4	25-60	25-60	35-65	45-70	60-80	80-100	100
No. 8	20-50	15-45	20-50	25-55	35-65	65-100	95-100
No. 16	---	---	---	---	---	40-80	85-100
No. 30	---	---	---	---	---	20-65	70-95
No. 50	8-30	3-18	5-20	5-20	6-25	7-40	45-75
No. 100	---	---	---	---	---	5-20	20-40
No. 200	4-12	1-7	4-10	4-10	4-10	4-10	9-20
	ASPHALT CEMENT, WEIGHT PERCENT OF TOTAL MIXTURES						
	3.5-8	4-8.5	4-9	4.5-9.5	5-10	7-12	8.5-12

Formula for job mix. The Contractor shall submit for the Engineer's approval on forms supplied by the department, a job mix formula for each mixture required for the project, a statement naming the source of each component, and a report showing the results of the applicable tests specified in a table 3-B. The job mix formula, including the tolerances shown in table 3-A(1), shall be within the master range specified in table 3 for the particular type of bituminous concrete.

TABLE 3-A(1) TOLERANCES FROM JOB MIX FORMULA FOR INDIVIDUAL SAMPLES

GRADATION MIX NO.	1	2	3	4	5	6	7
SIEVE SIZE	TOLERANCE (PLUS OR MINUS) PERCENTAGES						
No. 8	8	6	5	5	5	8	-
No. 50	5	4	4	4	4	4	8
No. 200	2.0	2.0	2.0	2.0	2.0	2.0	2.0
ASPHALT	.6	.6	.5	.5	.5	.5	.5

TABLE 3-A(5) TOLERANCES FROM JOB MIX FORMULA FOR AVERAGE OF 5 SAMPLES

GRADATION MIX NO.	1	2	3	4	5	6	7
SIEVE SIZE	TOLERANCES (PLUS OR MINUS) PERCENTAGE						
No. 8	4.0	3.0	2.5	2.5	2.5	4.0	
No. 50	2.5	2.0	2.0	2.0	2.0	2.0	2.0
No. 200	1.0	1.0	1.0	1.0	1.0	1.0	1.0
ASPHALT	.30	.30	.25	.25	.25	.25	.25

TABLE 3-B. DESIGN AND CONTROL REQUIREMENTS

MIX NUMBER	1		2	3	4	5	6	7
	STONE	GRAVEL						
CRITERIA	TEST LIMITS							
DESIGN STABILITY, LBS. MIN.	1500	1100	1200	1400	1300	1200	---	---
CONTROL STABILITY, LBS. MIN.	1200	800	900	1100	1000	900	---	---
FLOW VALUE .01	6-18	6-18	6-18	6-16	6-16	6-16	---	---
DESIGN AIR VOIDS % (NOTE 2)	3-7	3-7	3-7	3-6	3-6	3-6	3-8	3-6
CONTROL AIR VOIDS PERCENTAGE (NOTES 1 AND 2)	2-10	2-10	2-10	2-10	2-10	2-10	2-12	2-10

FOR ANY LOT OF BITUMINOUS CONCRETE WHICH IS NECESSARILY LESS THAN 1500 TONS, THE TEST RESULTS OF THE INDIVIDUAL SAMPLES SHALL CONFORM TO THE JOB MIX FORMULA WITHIN THE TOLERANCES OF TABLE 3-A(1). WHEN ANY SUCH LOT DOES NOT COMPLY WITH THIS REQUIREMENT, THE PAYMENT QUANTITY FOR THAT LOT SHALL BE REDUCED BY 5%.

TABLE 3-C 5-SAMPLE AVERAGES

DEVIATION OF 5-SAMPLE AVERAGE, PERCENT OF TOLERANCES IN TABLE 3-A(5)	REDUCTION OF PAYMENT QUANTITY PER LOT, PERCENT
0 to 100	NONE
101 to 150	5
151 to 200	10
OVER 200 (See Note 2)	15

NOTE 1 - WHERE MORE THAN ONE ADJUSTMENT OF PAYMENT QUANTITIES FROM THE ABOVE TABLES IS APPLICABLE TO A LOT, USE ONLY THE GREATEST SINGLE ADJUSTMENT FOR NON-CONFORMANCE TO THE JOB-MIX FORMULA.

NOTE 2 - THE ENGINEER MAY ORDER THE REMOVAL, AT THE CONTRACTOR'S EXPENSE, OF ANY MATERIAL SUBJECT TO THE MAXIMUM ADJUSTMENT OF PAYMENT QUANTITY SHOWN IN TABLE 3-C.

CONFORMANCE TO THE CONTROL STABILITY REQUIREMENTS SPECIFIED IN TABLE 3-B SHALL BE ASCERTAINED FROM ONE STABILITY DETERMINATION FOR EACH LOT OF MATERIAL. THE MATERIAL FOR THE STABILITY DETERMINATION SHALL BE OBTAINED AT THE MIXING PLANT AT THE SAME TIME THAT ONE OF THE RANDOM SAMPLES IS TAKEN.

TABLE 3-D ADJUSTMENT OF PAYMENT QUANTITIES PER LOT OF BITUMINOUS CONCRETE DUE TO NONCONFORMANCE TO STABILITY REQUIREMENTS.

DEVIATION OF LOT STABILITY BELOW CONTROL STABILITY OF TABLE 3-B (LBS)	REDUCTION OF PAYMENT QUANTITY (PERCENT)
0 to 100	5
101 to 200	10
OVER 200	20

CONFORMANCE TO THE CONTROL AIR VOIDS SPECIFIED IN TABLE 3-B SHALL BE DETERMINED ON THE BASIS OF ONE AIR VOIDS MEASUREMENT FOR EACH LOT OF APPROXIMATELY 2000 SQUARE YARDS A SINGLE RANDOM CORE FROM THAT LOT.

TABLE 3-E

MIX NUMBER	DEVIATION OF LOT, ABOVE CONTROL AIR VOIDS (PERCENT)	DEVIATION OF LOT, BELOW CONTROL AIR VOIDS (PERCENT)	REDUCTION OF PAYMENT QUANTITY (PERCENT)
1 AND 2	0.0 to 0.7	- - - - - - - - -	5
	0.8 to 1.5	0.0 to 0.5	10
	OVER 1.5	OVER 0.5	20
3,4,5,6, and 7	0.0 to 1.0	- - - - - - - - -	5
	1.1 to 2.0	0.0 to 0.5	10
	OVER 2.0	OVER 0.5	20

PRODUCER B

Producer B is located in central New Jersey and has six hot-mix plants at three locations and two quarries. Before the new specifications, there was one quality control employee whose primary function was control of the quarry operations. In 1967, a new asphalt testing laboratory was constructed and, over the next 2 years, an additional four employees were hired. All state mixes at this time were produced with bank-run sand and quarried stone. Trial mix designs were set up based on the new specifications and used the unprocessed quarry screenings (stone sand). These mixes were used in all commercial work. Raw-aggregate, hot-bin, extraction, and Marshall data were collected. Standard deviations were developed for the commercial mixes in production. These deviations were beyond those set out in the November 1968 Addenda A. Efforts were made to correct this problem. Attempts were made to better control both the gradation and the feeding of raw materials at the plant. A more elaborate sampling technique was tried. A program to "reeducate" plant operators was begun. Emphasis was placed on consistent cold-feed control and improved methods of storing and handling raw aggregate. An automatic compactor and a larger extractor were purchased for the laboratory. As a result, the standard deviation was reduced in 1969, but material was still often found to be outside the limits of the new specifications.

PRODUCER C

Producer C is located in south-central New Jersey. They had three asphalt plants at two locations and a natural sand pit. They had no quality control employees; instead, all work was contracted out to a consultant. Thus, quality control work was performed only when the project required it. This producer ran one of the few large jobs [approximately 136 078 Mg (150 000 tons)] under the January 1968 Addenda A. A new 3.6-Mg (4-ton) plant and a new laboratory were built for this job. The mix designs were set up with quarried stone and bank-run sand from the producer's pit located adjacent to the mix plant. Since the only sampling specified at this time was one roadway core (for composition, thickness, and density) for every 3000 yd^2, the consultant set up his own sampling program at the plant as follows:

1. Minimum of one set of raw-aggregate gradation daily,
2. Minimum of one set of hot-bin gradation daily,
3. Minimum of two extractions daily, and
4. Minimum of two sets (three plugs) of Marshall specimen daily.

The daily rate of production for the plant was between 1089 and 1633 Mg (1200 and 1800 tons). The mix was considered under control if the results fell within the tolerance for individual samples. Since this earliest specification had no averaging or penalty provision, no consideration was given at this time to statistical control.

Three major problems became apparent as the job progressed. The first was a lack of management supervision of plant operation. A relatively inexperienced operator was left to manage the plant by himself. Cold-feed calibration settings were rarely followed. An unsupervised loader operator allowed cold-feed bins to run out of material. Little or no action was taken by the supervisor-dispatcher when quality control problems were reported. In one instance, the plant ran in an "out-of-control" situation with variable carryover of 12.7-mm (0.5-in) material in bin 4 for 3 d before the general superintendent appeared and discovered the hole between the bin 3 and bin 4 compartments. The state inspector was not concerned since he considered this an end-result specification in that cores taken from the road would have to fail before the material would be considered unacceptable.

The second problem to develop during the course of the job was the variability of the bank-run sand. Although some borings of the pit had been taken, either a rational mining plan was never established by the producer or the material was too inherently variable. The end result was high variability on all three of the acceptance sieves [2.36, 0.3, and 0.075 mm (no. 8, no. 50, and no. 200)] in the final mix.

The third problem concerned the metering of mineral filler into the mix. Either the filler delivery system was too large, or the electromechanical control was too coarse. In any case, sample-to-sample variance outside the 2.0 percent tolerance of the specification was common on the 0.075-mm (no. 200) sieve.

The variances on the 2.36- and 0.3-mm (no. 8 and no. 50) sieves were equally high. Initially, the consultant followed the standard procedures of "quartering" the mix sample to reduce it to testing size. When high variance was found on the 2.36-mm sieve, the "grab" method of sampling was tried simultaneously as an alternative. In this case, one pan of material was taken from the truck from three levels of conical pile by using small shovels. A grab sample was carefully taken from the pan in a large grain scoop. Then the same pan of material was quartered in the usual way, and another sample was taken. Extractions were run on both samples. Sample-to-sample variance on the 2.36-mm sieve for the grab samples was about half as great as that for the quartered sample.

Although the use of the grab method reduced the variance on the 2.36-mm sieve, samples would still fall outside the tolerance with some regularity. This was usually attributable to raw-aggregate and cold-feed variances that were well beyond the tolerances and in many cases out of control. At times, the bank-run sand would alternate over a range more than twice the tolerance during the course of a single day. Although efforts were made to monitor and control this material, it was often out of control.

Producer C had another, older plant located in their central yard that produced material under the November 1968 specifications during this period. This plant used a bank-run sand from another source and was under the direct supervision of the chief superintendent. During this same period, this plant produced material with a sample-to-sample variance on the 0.3- and 0.075-mm (no. 50 and no. 200) sieves about half that of the newer plant. The same consultant was used for mix design and quality control in both plants.

PRODUCER D

Located in the southern part of the state, producer D operated one asphalt plant and a natural sand pit. Before 1968, they had no quality control run on their material other than that performed by the state inspector. With the advent of the new specifications a consultant was hired to do the mix design and quality control work. The only time quality control testing was performed was when the plant was supplying a state project. The mix designs were very similar to those under the old specifications. The producer's own bank-run sand and a quarried stone and mineral filler were used. The same daily testing program established by the consultant for producer C was again implemented here. Since most work for this plant came under the November 1968 revision of Addenda A (which included the statistical concepts), additional extractions were run on each lot sample. These extraction results soon became the primary data for quality control because of the penalty provision in the specifications. The problems encountered at this plant were twofold: first, the lack of respect for the quality control process on the part of the owners; and second, the variability of the bank-run sand. The owner would generally tell the batch man to run "light on filler and heavy on sand." The more expensive items in the mix in this case were filler and stone. This made effective quality control by the consultant quite difficult since no meaningful mix changes could be implemented until the owner was convinced it was necessary. Another common practice was to "top" trucks (i.e., mix only the final top loads in the truck according to design). On several occasions, the plant ran out of mineral filler and yet continued to ship material to the job. The bank-run sand, although fairly consistent, did tend to shift enough over time to require design revisions on the amount passing the 0.3-mm (no. 50) sieve.

PRODUCER E

Located in southeastern New Jersey, producer E operates one asphalt plant. Before 1968, this company had no quality control personnel. The mixes at this time were designed with natural sand, which was readily available. With the coming of Addenda A, a consultant was hired for the design and quality control work. In this case, the owner and plant superintendent took a strong interest in the quality control program. Suggestions made by the consultant were acted on promptly. Yard personnel and operators were given an understanding of what the quality program was about and materials were purchased with some consideration as to their quality.

Basically, the same quality control program outlined previously for producer C was again used here. In this case, control charts were used for the raw materials and mix analysis. A desired range for the raw materials was established based on the mix design and, when trends outside the range became apparent, calls were made to the suppliers to correct the problem. As deviations from the job-mix mean became apparent, small adjustments were made in the mix formula.

The only serious problem the consultant found was in the variance between the field and the central laboratory. In one instance, when the central laboratory reported a lot failure, the consultant witnessed the running of the "referee" sample at the central laboratory. Under this system, the mix sample was divided at the plant into three portions. The first went to the central laboratory for analysis and was considered the sample of record. The second was run by the producer's quality control person at the plant. The third was tagged, sealed, and stored as a referee sample.

The central laboratory had a policy of running only one ash correction per lot of material on their centrifuge extraction. When ash corrections were run on all samples in the lot, all passed and conformed fairly closely with the results obtained at the plant.

This producer succeeded in running several medium-sized [36 360-Mg (40 000-ton)] jobs without penalties under the new specification.

SUMMARY OF 1968-1970 PERIOD

In summary, it seemed that during this period only a few producers fully comprehended the ramifications of the new specifications and most felt they could get by without any changes in their basic operations. Quality control data were generally viewed with skepticism by the few producers who could comprehend it. Generally speaking, the few comprehensive quality control programs (those including raw-aggregate and hot-bin data and regular visual plant inspection) fell prey to the demands of the end-result process. The extraction sample of record (and, to a lesser degree, the Marshall sample) became the dominant indicator of mix quality. In the beginning, there was generally a poor understanding at the field level of the statistically based two-tolerance system. Most quality control personnel soon realized that mixes had to be controlled on the lot tolerance (average of five) and not on the individual tolerances.

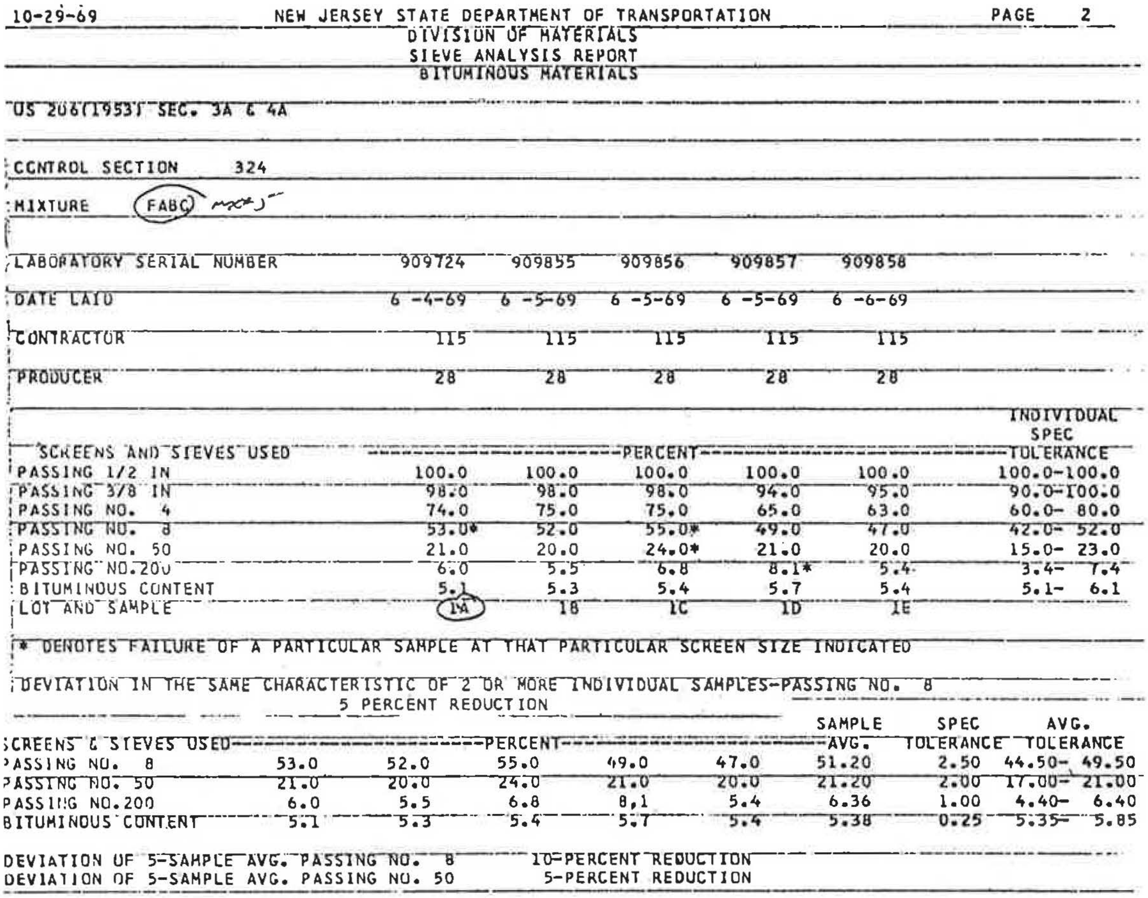
Extractions run in the field were often considered acceptable if they fell within the tolerance for individual samples (which was twice as wide as that for the lot average). On several early jobs it seemed that passing results were being obtained, but at the end of those jobs it was found that the lot failed on the basis of the average of five.

In spite of this, few if any charts were kept of process control data. In fact, when the department distributed control charts in 1970 and required their use, there was so much resistance on the part of both producers and state personnel that the program faded out of existence a year later. The only significant collecting and publishing of data were done by the department in the job printout, an example page of which is shown in Figure 2. Most process control continued to be based on the variances of the individual samples in a lot. Technicians generally reviewed the individual sample result and made "judgment calls" as to whether the formula needed to be adjusted. Depending on the technician, these judgment calls may have been based on overall plant operations (variance in raw aggregate and screening problems) or simply the results of the last extractions.

In late 1969, the New Jersey DOT did a study of projects completed under the new specification (1). It found that 17 of the 35 lots included in the study failed to comply and were subject to penalties. Approximately 75 percent of the failures were for composition, and the remaining failures were equally divided between core air voids and Marshall stability. An evaluation of the average standard deviations for the projects showed that they were equal to or less than those used in developing the specification. Thus, the state concluded that excessive variance was not the cause of the failures but rather multilaboratory testing variance and the inability of the producer's quality control process to keep his process average target on the job mix. This was amply demonstrated by the fact that central laboratory results showed a consistent variation from producers' laboratory results on duplicate samples. At the same time, the producers' own results showed that they often failed to meet the average of five sample tolerances based on their own design. In the area of composition testing, most samples failed because they missed the target values and not because they were excessively variable. The state attributed this to the lack of experience of the producers' quality control personnel or "inexactness in the designing of the mix" or both.

From the producer's viewpoint, there appeared to be several problem areas with the new specification. First, there was the problem of the difference between the sample run at the plant laboratory, on which all quality control was based, and the sample run at the department's central laboratory, on which all payments were based. Next, there was the problem of adjusting the mix design for variations in raw materials. Under the 1968 Addenda A, the lengthy process of submitting a new design was the only method of making adjustments [this was partic-

Figure 2. Page from New Jersey Department of Transportation job printout.



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                                  DIVISION OF MATERIALS
                                  SIEVE ANALYSIS REPORT
                                  BITUMINOUS MATERIALS

US 206(1953) SEC. 3A & 4A

CONTROL SECTION      324

MIXTURE     FABC

LABORATORY SERIAL NUMBER            909724    909855    909856    909857    909858

DATE LAID                          6 -4-69   6 -5-69   6 -5-69   6 -5-69   6 -6-69

CONTRACTOR                             115       115       115       115       115

PRODUCER                                28        28        28        28        28

                                                                                    INDIVIDUAL
                                                                                       SPEC
  SCREENS AND SIEVES USED      ----------------------PERCENT-------------------------TOLERANCE
PASSING 1/2 IN                      100.0     100.0     100.0     100.0     100.0    100.0-100.0
PASSING 3/8 IN                       98.0      98.0      98.0      94.0      95.0     90.0-100.0
PASSING NO.  4                       74.0      75.0      75.0      65.0      63.0     60.0- 80.0
PASSING NO.  8                       53.0*     52.0      55.0*     49.0      47.0     42.0- 52.0
PASSING NO. 50                       21.0      20.0      24.0*     21.0      20.0     15.0- 23.0
PASSING NO.200                        6.0       5.5       6.8       8.1*      5.4      3.4-  7.4
BITUMINOUS CONTENT                    5.1       5.3       5.4       5.7       5.4      5.1-  6.1
LOT AND SAMPLE                         1A        1B        1C        1D        1E

* DENOTES FAILURE OF A PARTICULAR SAMPLE AT THAT PARTICULAR SCREEN SIZE INDICATED

DEVIATION IN THE SAME CHARACTERISTIC OF 2 OR MORE INDIVIDUAL SAMPLES-PASSING NO.  8
                    5 PERCENT REDUCTION
                                                                     SAMPLE     SPEC       AVG.
SCREENS & SIEVES USED----------------------PERCENT--------------------AVG.  TOLERANCE  TOLERANCE
PASSING NO.  8            53.0      52.0      55.0      49.0      47.0    51.20      2.50  44.50- 49.50
PASSING NO. 50            21.0      20.0      24.0      21.0      20.0    21.20      2.00  17.00- 21.00
PASSING NO.200             6.0       5.5       6.8       8,1       5.4     6.36      1.00   4.40-  6.40
BITUMINOUS CONTENT         5.1       5.3       5.4       5.7       5.4     5.38      0.25   5.35-  5.85

DEVIATION OF 5-SAMPLE AVG. PASSING NO.  8          10-PERCENT REDUCTION
DEVIATION OF 5-SAMPLE AVG. PASSING NO. 50           5-PERCENT REDUCTION
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ularly applicable on the 0.3-mm (no. 50) sieve]. Next, there was a general feeling that the tolerances were not broad enough to contain normal variation, a desire to have more than just the three plugs per lot on the stability determination, and a desire for a modification in the basic gradation tables to allow the use of a wider variety of raw materials.

Shortly after the completion of the 1969 study, the department began to allow the acceptance of "retroactive designs." These could be submitted by the producer after he reviewed the lot data from the central laboratory. Retroactive designs could be submitted on a lot-to-lot basis and were intended to compensate for multilaboratory testing variance. This required nothing more than a letter requesting a numerical change on a particular sieve.

In September 1970, a new revision of the 1968 Addenda A was published. Known as the "yellow Addenda A," it contained the following revisions:

1. Changes in the basic gradation tables;
2. An increase in the gradation and asphalt cement (AC) tolerance for both the individual and average (in addition, the penalty provision for failing to comply with the individual sample tolerance was removed);
3. Plant acceptance, i.e., the final acceptance of material for gradation, AC content, and Marshall stability based on the plant technician's field results (these tests had to be carefully documented on forms supplied by the department and witnessed by the state inspector);
4. A tightening up of the air-void limits for both design and field core samples;
5. An increase in the number of specimens used for the Marshall stability criteria (one plug would be made and tested for each of the sublot samples, and the average of five would have to meet the minimum specified for control);
6. A reduction in the amount of the penalty for nonconformance; and
7. A limitation on the use of unwashed natural fine aggregates.

Also included in the yellow Addenda A was a detailed description of the various testing procedures to be followed.

The above changes seemed to resolve most of the problems that had plagued the first Addenda A. Although the policy of allowing retroactive design changes eliminated many composition penalties, the department was less than enthusiastic about this approach. It was felt that this policy encouraged an even greater lack of control by the producer. Thus, late in 1971, the department changed its policy and allowed design changes only at the beginning of a lot.

The inclusion of a natural sand requirement that effectively eliminated the use of bank-run sands disturbed most of the producers in the South Jersey area. The department's action was the result of several pavement failures attributed to clay "pop-outs" in mixes that used bank-run sand.

With the advent of "plant acceptance," many producers' technicians seemed to have more confidence in the statistical specification since the results they got were now considered record. Further confidence was gained as a result of the wider tolerances and the rela-

Table 2. Summary of average composition parameters under Addenda A.

	Average Standard Deviation (%)				Average Absolute Difference in Job Mix Mean (%)		Standard Deviation Plus Difference[b] (%)		
Mixture Characteristic	1969 Green Addenda	1970-1971 Green Addenda	1971 Yellow Addenda	Current Tolerance[a]	1969 Green Addenda	1971 Yellow Addenda	Calculated	Rounded to Account for Test Precision	Recommended New Specification Tolerance for Five-Sample Average (%)
Mix 1									
Sieve									
No. 8	3.75	3.34	3.31	4.0	1.69	1.10	4.41	4.5	4.5
No. 50	2.01	2.08	1.93	2.5	1.26	0.47	2.40	2.5	3.0
No. 200	1.18	0.96	1.10	1.0	0.39	0.25	1.35	1.4	1.4
Average composition	0.35	0.33	0.34	0.35	0.11	0.07	0.41	0.40	0.45
Mix 2									
Sieve									
No. 8	2.91	2.90	2.77	3.00	1.91	0.92	3.69	3.5	4.0
No. 50	1.87	1.67	1.58	2.00	1.21	1.10	2.68	2.5	3.0
No. 200	0.99	0.82	0.89	1.00	0.51	0.37	1.26	1.3	1.4
Average composition	0.34	0.32	0.25	0.35	0.13	0.12	0.37	0.35	0.45
Mix 5									
Sieve									
No. 8	3.28	2.74	2.70	3.0	0.36	0.80	3.50	3.5	4.0
No. 50	2.42	2.28	1.92	2.5	0.81	0.90	2.82	3.0	3.0
No. 200	1.13	0.95	1.10	1.0	0.44	0.18	1.28	1.3	1.4
Average composition	0.30	0.26	0.26	0.30	0.11	0.17	0.43	0.45	0.45

[a] Average of five samples. [b] 1971.

tive ease of adjusting designs for normal variation in raw materials.

Process control in the average asphalt plant was not affected, however. Since most technicians were already normally sampling and testing the duplicate record sample under the "green Addenda A," the control process continued to be based on the extractions taken for record. Control at the plant may indeed have become somewhat more lax. Since the plant technician's samples were the sample of record, he could now run closer to the limits of the tolerance and not fear that the sample run in the central laboratory might be out. He could also make mix adjustments that would compensate for samples that fell outside the limit. Since there was no longer any limitation on the individual samples, he could intentionally make material out of tolerance to bring the average of five in range.

Again in 1972, the department reviewed the results of Addenda A. Afferton (2) observed that there was generally a decrease in variability since the 1969 study (Table 2). He pointed out that in spite of this one out of seven lots was still penalized. As in the earlier study, he attributed this to the producer's inability to meet his or her own job mix formula. Although some increase was observed in the producer's ability to hit the target value, Afferton generally discounted this as the result of the shift in testing laboratories. He further observed (2) that "marked changes in the producer's ability to evaluate stockpile aggregate and use statistical techniques would be needed to effect . . . improvement." He felt that this would be a difficult and time-consuming process that may not be necessary since historical data suggest that the current differences in the job mix mean are comparable in magnitude to those that occurred before Addenda A when the department had complete control of plant production. As a result, a wider tolerance range was proposed for mixture composition.

Finally, in May 1973, another version of Addenda A was released. The changes represented by "blue Addenda A" were as follows:

1. Deletion of the tolerance for individual samples,
2. Inclusion of "tolerances for the range of five samples," and
3. An increase in all of the tolerances for the average of five samples.

These changes seemed to have effectively corrected the problem outlined above.

CONCLUSIONS

Because Addenda A changed so many things all at once, it is difficult to isolate the effects of the statistical process control aspect of the new specification. Ensuring that the changes in requirements for gradation and raw aggregates had a substantial effect on the asphalt mixes (whether for better or worse) would be a subject for another paper. One thing appears certain: After the application of the first penalties, nearly all producers took a keen interest in the Addenda A specification. Some were inherently skeptical and continuously sought to find defects in the specification rather than defects in the product. A few were more willing to accept the system and generally strove to control the product better. The latter seem to have fared rather well even under the earlier, more restrictive version of Addenda A.

In any event, the producer's attitude toward process control is critical to its effective application. If the producer is not convinced of the necessity or the desirability of the system, it is virtually impossible to effectively carry out a good program. No matter how competent and enthusiastic the technician may be, he can only do what the rest of the organization is geared to do.

As in any good system of process control, testing error must be kept in line with the limits allowable by the tolerance. In addition, a standardized and practical testing procedure must be published and understood by the technicians. A certain level of confidence must be established and maintained between quality control testing and acceptance testing.

It is essential, therefore, that careful consideration be given to the establishment of realistic tolerances and penalties. Since the person who pays the penalty often has little or no understanding of testing or quality control technology, that person tends to quickly judge the system in black-and-white terms. He or she generally has neither the time nor the inclination to determine why samples pass or fail. If a producer suddenly finds that he or she is being penalized often and that fellow producers are in the same position, then the credibility of the system will soon be in question. Once this occurs, it becomes very difficult for the technician effectively to keep the products under control within the system. If at the same time the technician lacks confidence in the testing and acceptance procedures, the system virtually disintegrates.

Under these circumstances, when the acceptance point is at the plant, the propensity for graft is greatly increased. When the acceptance is more distant (as in the case of cores taken from the finished product and tested in central laboratories), more involved legal battles are often encountered. In any event, the theory and practice of good statistically based quality control are completely undermined. I feel that this was the status of the Addenda A specification just before the release of the 1970 yellow Addenda A.

It is important that good delineation and coordination be established between acceptance testing and quality control testing. A good quality control program should be somewhat independent of the acceptance system. Under the existing Addenda A, acceptance testing dominates and indeed, in most cases, overpowers what I consider to be good quality control testing. In plants that have lower rates of production, there is a tendency not to do any testing until a "lot sample is due" because of the strong emphasis on acceptance samples. Indeed, if tolerances were properly established and confidence in correlation with central laboratory testing was ensured, I would rather see acceptance testing performed by the central laboratory from field samples. However, I do not wish to minimize the problem of developing such a system (especially the problem associated with a central laboratory type of operation such as that used in New Jersey in recent years). If such a system could be effectively developed, however, a more comprehensive quality control program could be used at the plant where the technician could monitor the entire operation and not just some narrow aspect of it.

Essentially, a statistically based quality control program is a vast improvement over the typical one-sample (pass or fail) system of the past. If it is to be truly effective in maintaining the quality of the product, confidence in the system must be upheld by the establishment of realistic tolerances and testing methods. It is essential that all of the involved parties thoroughly understand the theory and application of the system.

REFERENCES

1. K. Afferton. New Jersey Department of Transportation Standard Specification Analysis—1969 Addenda A. New Jersey Department of Transportation, Jan. 1970.
2. K. Afferton. Composition and Air Void Requirements for Bituminous Mixtures. New Jersey Department of Transportation, Memorandum Rept., July 7, 1972.

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Process Control of Mineral Aggregates

John T. Molnar, Standard Slag Company, Youngstown, Ohio

An aggregate process control program currently used by a multiplant aggregate producer is described. The success of the program is credited to the rapid feedback of test data directly to plant management. The program uses district and plant laboratories staffed with from one to three technicians for conducting daily tests for gradation control and a central laboratory for determining other important properties of aggregates and the products in which they are used. Benefits of the program—including savings that result from minimizing rejections, improved customer relations, and other services performed by the responsible department—are emphasized. The importance of a working knowledge of basic statistical concepts by both aggregate technicians and plant management is stressed.

The process control system described in this paper is used to control the quality of aggregates at 21 plants of the Standard Slag Company. These include 11 blast furnace slag plants, 5 limestone plants, and 5 sand and gravel plants. The program is directed by the Materials Control and Research Department with a staff of 20 full-time and 5 part-time employees. Testing facilities include six district and plant laboratories, each staffed with from one to three technicians and equipped to conduct daily determinations for gradation and unit weight, and a central laboratory equipped for determining most physical and chemical properties specified for the aggregates as well as the performance of the finished products in which the aggregates are used.

Since gradation is the primary aggregate property over which the plant manager has control and since failure to comply with the specified gradation is the primary cause for rejecting aggregate from approved sources, this paper deals primarily with the control of aggregate gradation during production, handling, and recovery from stock.

The founders of our organization realized more than 50 years ago the benefits of producing quality aggregates in terms of a favorable return on investment and repeat sales. During our first encounter with statistical or end-result specifications during the late 1960s, it became apparent that increasing the effectiveness of our process control system would be a sound investment in terms of minimizing costly rejections and product liability claims and improving customer relations by supplying aggregates that have a minimal variation in specified properties. Accomplishing this meant devising a system of rapid testing and reporting that would provide immediate feedback of production control test results to plant management so that process adjustments, when necessary, could be implemented and checked for their effectiveness before a sizable quantity of nonspecification material was produced. The system now in effect was presented to the company's executive committee and received their total support.

The basic procedure used for gradation control is shown in Figure 1. Basically, each aggregate size processed in each operation is sampled in accordance with a prescribed sampling plan that stipulates sampling frequency and location and the minimum sample size. If the gradation of the sample complies with that specified, no adjustment is made. If the first sample fails to comply, a second sample is immediately selected to verify the results of the first and, at the same time, to

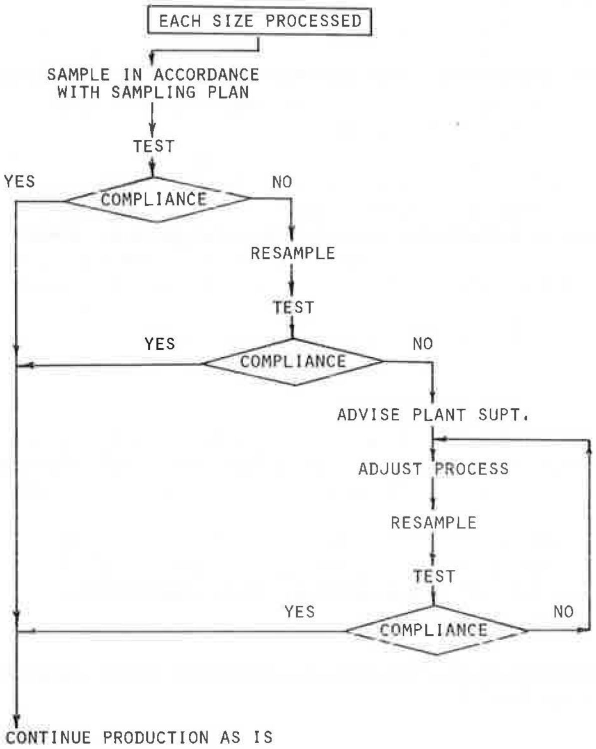


Figure 1. Procedure for gradation control.

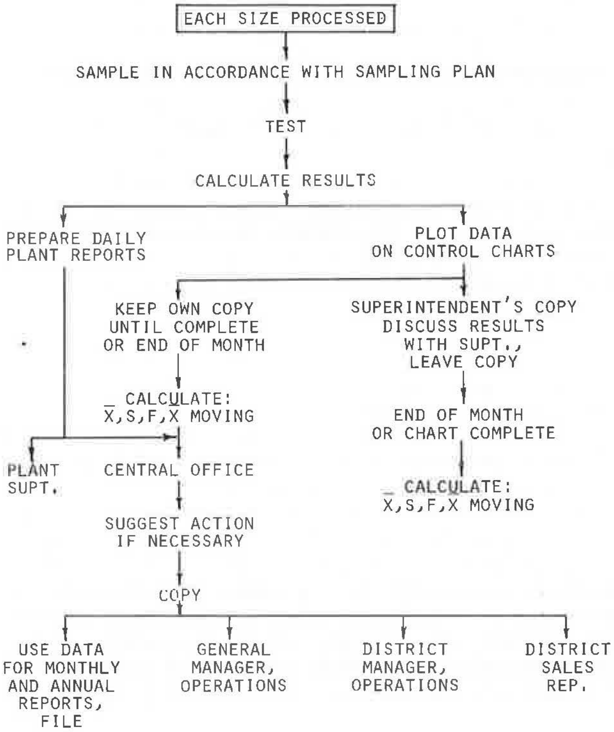
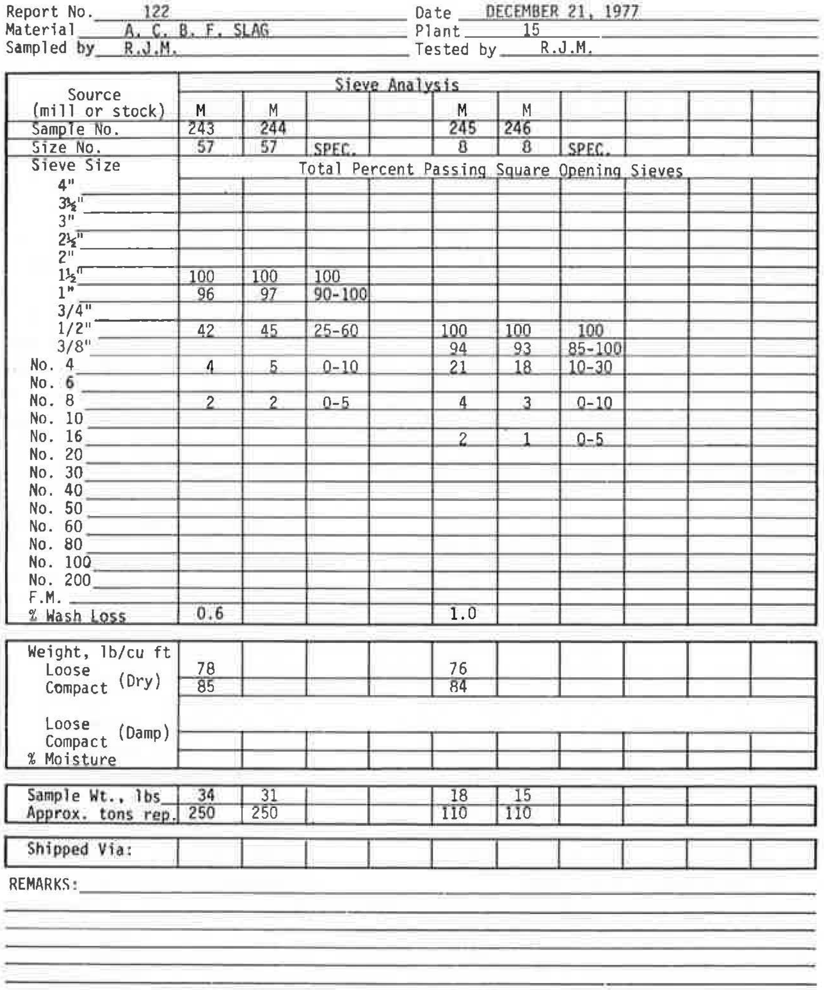


Figure 2. Responsibilities of district laboratory technicians.

Figure 3. Plant aggregate report.



Report No. 122
Material A. C. B. F. SLAG
Sampled by R.J.M.
Date DECEMBER 21, 1977
Plant 15
Tested by R.J.M.

	Sieve Analysis									
Source (mill or stock)	M	M			M	M				
Sample No.	243	244			245	246				
Size No.	57	57	SPEC.		8	8	SPEC.			
Sieve Size	Total Percent Passing Square Opening Sieves									
4"										
3½"										
3"										
2½"										
2"										
1½"	100	100	100							
1"	96	97	90-100							
3/4"										
1/2"	42	45	25-60		100	100	100			
3/8"					94	93	85-100			
No. 4	4	5	0-10		21	18	10-30			
No. 6										
No. 8	2	2	0-5		4	3	0-10			
No. 10										
No. 16					2	1	0-5			
No. 20										
No. 30										
No. 40										
No. 50										
No. 60										
No. 80										
No. 100										
No. 200										
F.M.										
% Wash Loss	0.6				1.0					

Weight, lb/cu ft										
Loose (Dry)	78				76					
Compact (Dry)	85				84					
Loose (Damp)										
Compact (Damp)										
% Moisture										

Sample Wt., lbs	34	31			18	15				
Approx. tons rep.	250	250			110	110				

Shipped Via:										

REMARKS:

Figure 4. Control chart.

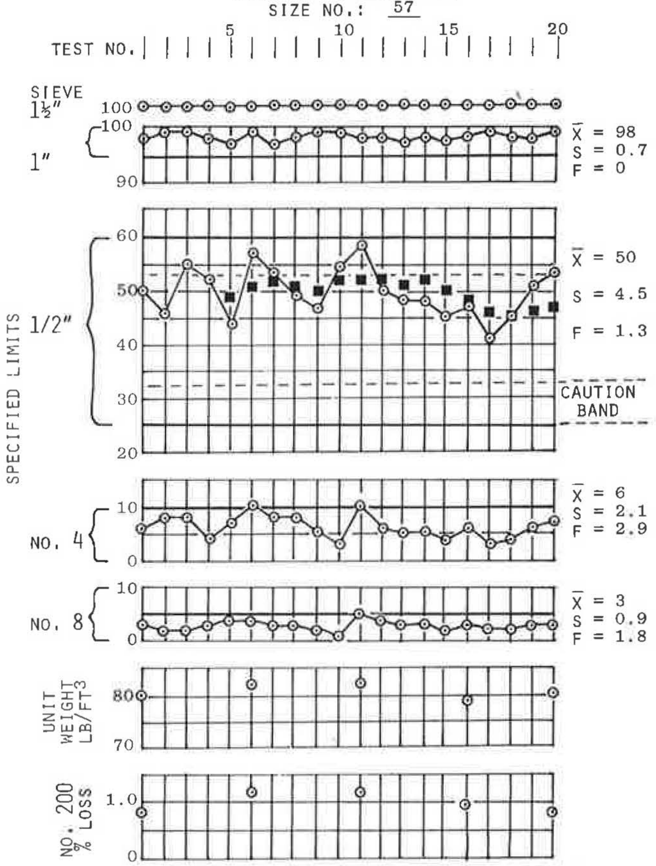
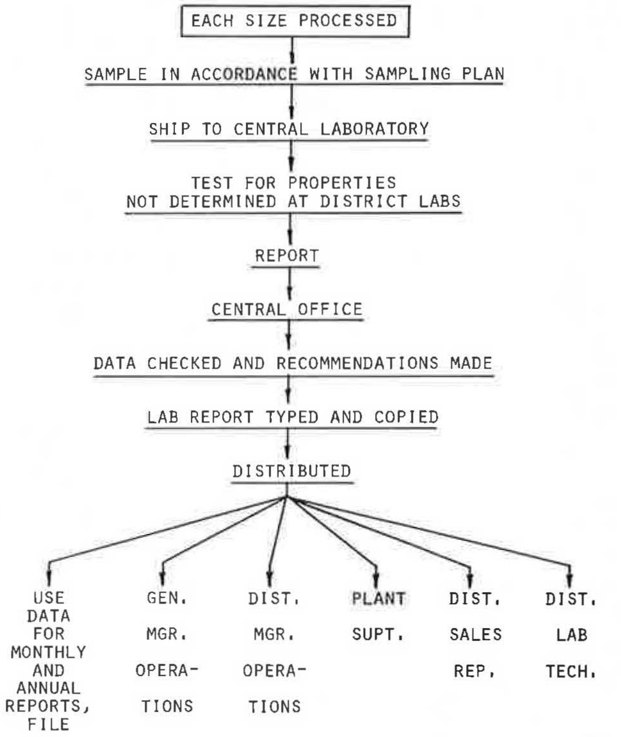


Figure 5. Sampling procedure for central laboratory tests.



reduce sampling or testing error. If the second sample also fails to comply with the specified gradation, the technician advises the plant superintendent that an adjustment in the process is necessary. Once the adjustment is made, the aggregate is resampled to confirm that the adjustment corrected the condition. If it did not, the adjustment process is continued until compliance with the specified gradation is achieved.

Figure 2 shows an outline of the responsibilities of the district laboratory technicians. It should be noted that sampling and testing encompass all of the steps outlined in Figure 1.

District technicians are responsible for calculating the test data and preparing two reports. The daily plant report (Figure 3) is a comparison of the gradations of current production with the specified gradings (because the reports cited here use U.S. customary units of measurement, no SI equivalents are given). To provide immediate feedback of test results, the technician discusses the results and supplies the plant superintendent with his or her copy immediately after completing the daily tests. The technician also sends a copy to the central office for further action and distribution as shown in Figure 2. In addition, immediately after completing the daily tests, the technician brings the control charts up to date. The control charts (Figure 4) show up to 25 sieve analyses of a given aggregate size and provide the plant superintendent with a running account of the variation of each size processed.

Again, to provide the necessary immediate feedback of test results to the plant superintendent, the technician keeps the superintendent's copies of the control charts in a looseleaf binder in the plant office and brings them up to date on the day the tests are conducted. The technician also brings his or her own copies up to date at the same time. Note that, besides the upper and lower specification limits for each sieve, caution bands are included to alert the superintendent that he or she may be operating too close to the specified limits.

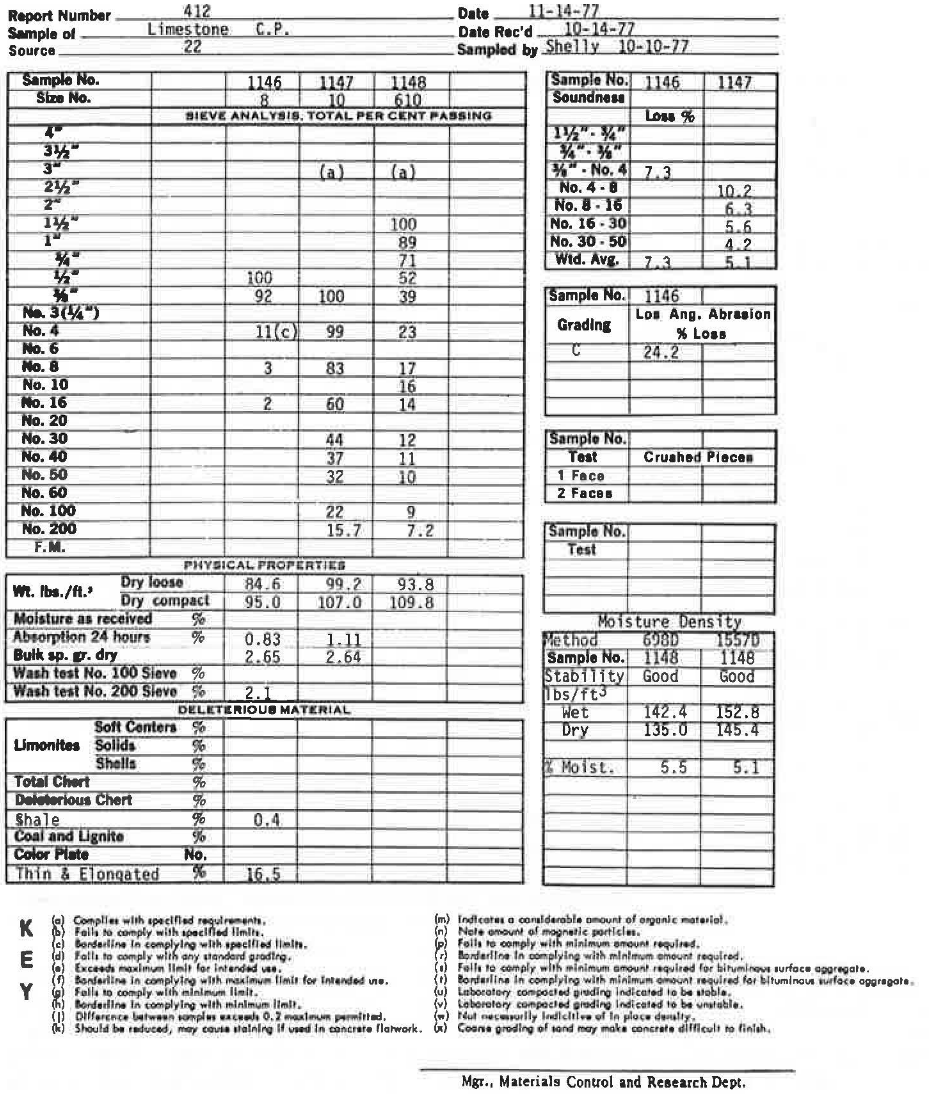
In preparing the control charts, a circle is plotted for each test result. Also, starting with the fifth test result, a square is plotted on the control sieve to represent the moving average of five results. The moving average reduces the variation of individual test results and is used to predict causes of potential problems, such as wear of production components.

At the end of each month, the technicians calculate the average, standard deviation, and potential failure for each sieve specified based on a normal curve. These figures are shown at the right of each plot. Each technician is provided with a statistical calculator for ease in determining these parameters. The technicians then send their copies to the central office (Figure 2) where, if necessary, further action is suggested. Copies are then distributed to the general manager of operations, the district manager of operations, and the district sales representative.

District technicians also select samples of all sizes produced at each operation at prescribed intervals and ship these to the central laboratory (Figure 5) to be tested for specified properties not determined at the district level. A typical laboratory report is shown in Figure 6.

The quality control program generates five reports. In addition to the daily plant report, the laboratory report, and the control charts already mentioned, the information from the daily plant reports are tabulated by the department secretaries on a monthly report (Figure 7). The average, standard deviation, minimum, maximum, range, and potential percentage of failure are computed by using a tape-programmed calculator. During December of each year, the data from the monthly

Figure 6. Interoffice aggregate report.



Report Number 412
Sample of Limestone C.P.
Source 22
Date 11-14-77
Date Rec'd 10-14-77
Sampled by Shelly 10-10-77

Sample No.		1146	1147	1148	
Size No.		8	10	610	
	SIEVE ANALYSIS, TOTAL PER CENT PASSING				
4"					
3½"					
3"			(a)	(a)	
2½"					
2"					
1½"				100	
1"				89	
¾"				71	
½"		100		52	
⅜"		92	100	39	
No. 3(¼")					
No. 4		11(c)	99	23	
No. 6					
No. 8		3	83	17	
No. 10				16	
No. 16		2	60	14	
No. 20					
No. 30			44	12	
No. 40			37	11	
No. 50			32	10	
No. 60					
No. 100			22	9	
No. 200			15.7	7.2	
F.M.					

PHYSICAL PROPERTIES

Wt. lbs./ft.³	**Dry loose**	84.6	99.2	93.8	
	Dry compact	95.0	107.0	109.8	
Moisture as received	**%**				
Absorption 24 hours	**%**	0.83	1.11		
Bulk sp. gr. dry		2.65	2.64		
Wash test No. 100 Sieve	**%**				
Wash test No. 200 Sieve	**%**	2.1			

DELETERIOUS MATERIAL

Limonites	**Soft Centers**	**%**				
	Solids	**%**				
	Shells	**%**				
Total Chert		**%**				
Deleterious Chert		**%**				
Shale		**%**	0.4			
Coal and Lignite		**%**				
Color Plate		**No.**				
Thin & Elongated		**%**	16.5			

Sample No.	1146	1147
Soundness		
	Loss %	
1½" - ¾"		
¾" - ⅜"		
⅜" - No. 4	7.3	
No. 4 - 8		10.2
No. 8 - 16		6.3
No. 16 - 30		5.6
No. 30 - 50		4.2
Wtd. Avg.	7.3	5.1

Sample No.	1146	
Grading	**Los Ang. Abrasion % Loss**	
C	24.2	

Sample No.		
Test	**Crushed Pieces**	
1 Face		
2 Faces		

Sample No.		
Test		

Moisture Density

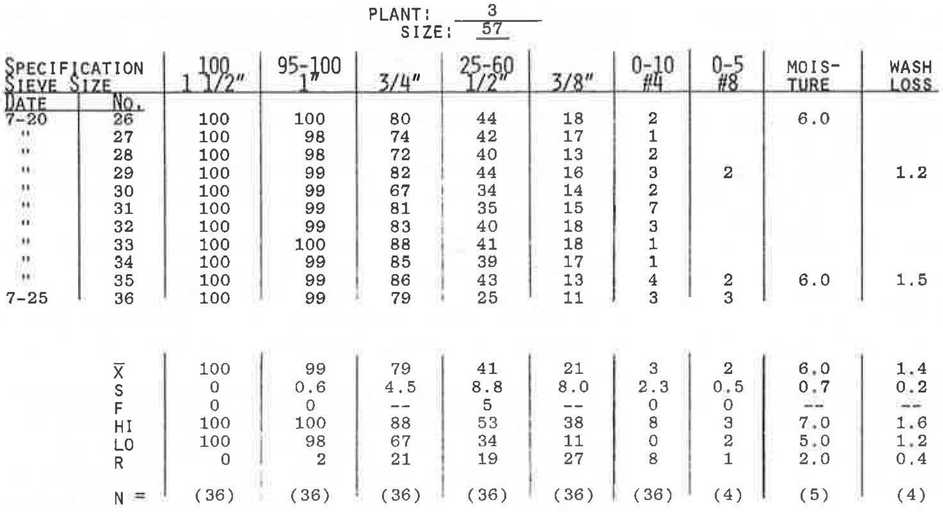
Method	698D	1557D
Sample No.	1148	1148
Stability	Good	Good
lbs/ft³		
Wet	142.4	152.8
Dry	135.0	145.4
% Moist.	5.5	5.1

KEY

(a) Complies with specified requirements.
(b) Fails to comply with specified limits.
(c) Borderline in complying with specified limits.
(d) Fails to comply with any standard grading.
(e) Exceeds maximum limit for intended use.
(f) Borderline in complying with maximum limit for intended use.
(g) Fails to comply with minimum limit.
(h) Borderline in complying with minimum limit.
(j) Difference between samples exceeds 0.2 maximum permitted.
(k) Should be reduced, may cause staining if used in concrete flatwork.
(m) Indicates a considerable amount of organic material.
(n) Note amount of magnetic particles.
(p) Fails to comply with minimum amount required.
(r) Borderline in complying with minimum amount required.
(s) Fails to comply with minimum amount required for bituminous surface aggregate.
(t) Borderline in complying with minimum amount required for bituminous surface aggregate.
(u) Laboratory compacted grading indicated to be stable.
(v) Laboratory compacted grading indicated to be unstable.
(w) Not necessarily indicitive of in place density.
(x) Coarse grading of sand may make concrete difficult to finish.

Mgr., Materials Control and Research Dept.

Figure 7. Monthly gradation report.



PLANT: 3
SIZE: 57

SPECIFICATION SIEVE SIZE		100 1 1/2"	95-100 1"	3/4"	25-60 1/2"	3/8"	0-10 #4	0-5 #8	MOIS- TURE	WASH LOSS
DATE	NO.									
7-20	26	100	100	80	44	18	2		6.0	
"	27	100	98	74	42	17	1			
"	28	100	98	72	40	13	2			
"	29	100	99	82	44	16	3	2		1.2
"	30	100	99	67	34	14	2			
"	31	100	99	81	35	15	7			
"	32	100	99	83	40	18	3			
"	33	100	100	88	41	18	1			
"	34	100	99	85	39	17	1			
"	35	100	99	86	43	13	4	2	6.0	1.5
7-25	36	100	99	79	25	11	3	3		
	$\overline{X}$	100	99	79	41	21	3	2	6.0	1.4
	S	0	0.6	4.5	8.8	8.0	2.3	0.5	0.7	0.2
	F	0	0	--	5	--	0	0	--	--
	HI	100	100	88	53	38	8	3	7.0	1.6
	LO	100	98	67	34	11	0	2	5.0	1.2
	R	0	2	21	19	27	8	1	2.0	0.4
	N =	(36)	(36)	(36)	(36)	(36)	(36)	(4)	(5)	(4)

Figure 8. Annual aggregate report.

LIMESTONE

PLANT: 18 MATERIAL SOURCE: 2

Material Size	57			8		
Physical Properties	Hi	Low	Avge.	Hi	Low	Avge.
Unit Weight, lb/ft^3						
Dry Loose	87.8	83.6	85.7	82.0	80.2	81.2
Dry Compact	98.0	93.6	95.6	91.8	89.6	90.7
Specific Gravity,						
Bulk Dry	2.52	2.45	2.49	2.48	2.42	2.46
Absorption, %	3.80	2.93	3.27	4.55	3.75	4.12
Moisture as Rec'd., %	7.0	4.0	5.6	8.0	5.0	6.7
Los Angeles Abrasion, % Loss						
B Grading	31.3	26.3	28.6			
C Grading				31.5	27.7	29.3
Soundness, % Loss	5.5	1.5	3.6	6.7	2.5	5.1
Shale, %	0	0	0	0	0	0
Thin & Elongated, %	3.2	1.6	2.4	9.3	5.0	7.5

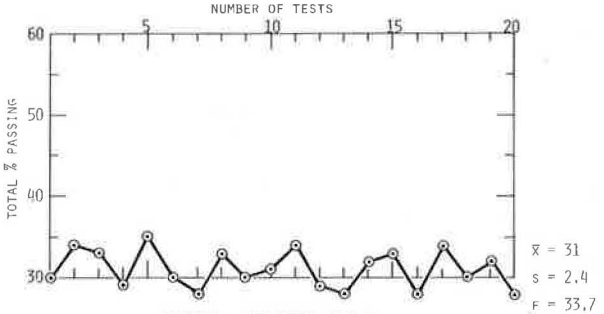
Chemical Properties

	57	8
Constituents	Total %	by Wt.
SiO_2	3.30	3.28
Al_2O_3	0.19	0.19
CaO	33.77	34.63
MgO	16.85	16.96
S	0.084	0.100
Fe_2O_3	0.12	0.15
Ign. Loss	44.61	44.38

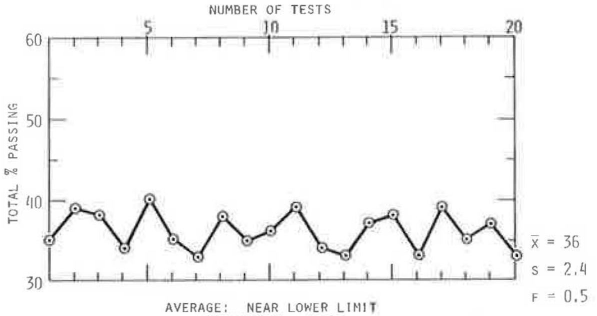
Average Gradation	57 N = 220							8 N = 108						
Sieve Size	Spec	Avge.	Hi	Low	R	S	F	Spec	Avge.	Hi	Low	R	S	F
1 1/2"	100	100	100	100	0	0	0							
1"	95-100	99	100	95	5	0.9	0							
3/4"		79	99	66	33	4.6								
1/2"	25-60	42	59	26	33	6.2	1	100	100	100	100	0	0	0
3/8"		18	43	5	38	5.8		85-100	95	99	88	10	1.7	0
#4	0-10	2	9	0	9	1.2	0	10-30	17	25	9	14	3.1	2
#8								0-10	3	5	2	3	1.0	0
#16								0-5	1	1	1	0	0	0
Wash Loss, %														
200 Sieve		1.1	1.3	0.7					1.0	1.6	0.5			

TOTAL PERCENT PASSING

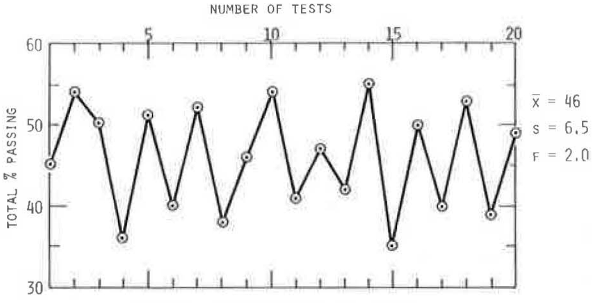
Figure 9. Example control charts used in training sessions.



AVERAGE: TOO CLOSE TO L.L.
VARIATION: LOW
1 OUT OF 3 SAMPLES FAIL

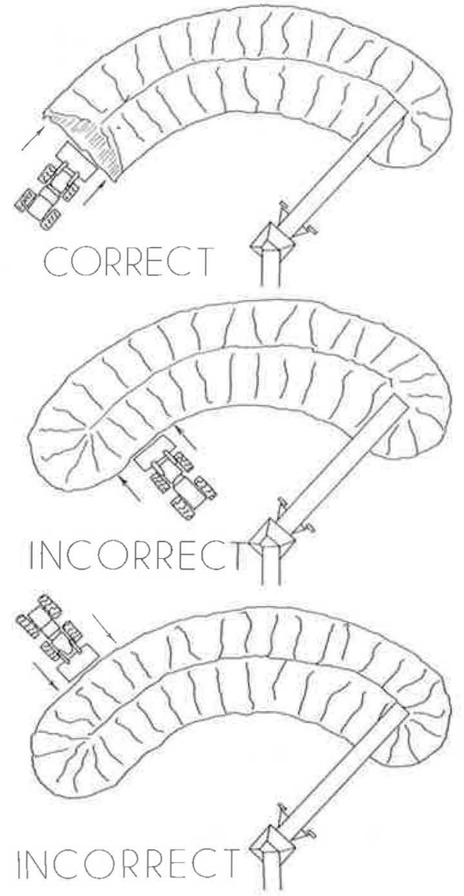


AVERAGE: NEAR LOWER LIMIT
VARIATION: LOW
EXCELLENT CONTROL



AVERAGE: NEAR MID-POINT OF LIMITS
VARIATION: MODERATE

Figure 10. Example stockpile-recovery training aids used in training sessions.



reports are used to construct an annual report for each plant (Figure 8). This report, which shows the yearly average and the variation of properties of each size aggregate processed at each plant, provides valuable data to the marketing, operations, and plant engineering departments as well as a comparison of the capability of each operation to maintain or upgrade the quality of its products.

As a means of continually upgrading the quality control program, all technicians and other members of the Materials Control and Research Department are required to annually attend a 2½-d seminar conducted at the central laboratory that includes sessions on new and proposed aggregate specifications, sampling and testing techniques, and basic statistics and reporting techniques. The technicians also attend seminars sponsored by state aggregate associations and qualify as registered technicians in those states that require certification.

So that the test data that result from the program are thoroughly understood, several half-day seminars that are conducted annually by personnel of the Materials Control and Research Department are held on a district basis for operating personnel and cover such areas as understanding control charts and stockpile recovery to minimize segregation. Typical training aids used in these sessions are shown in Figures 9 and 10.

In an effort to reduce sampling and testing time, we have incorporated automatic sampling and testing in our largest operation, which loads aggregate into lake vessels at 1090 Mg/h (1200 tons/h). At the touch of a button, a sample that weighs approximately 227 kg (500 lb) is sliced from a conveyor-belt transfer point, conveyed to a testing tower, split, sieved, and weighed in separate size fractions. In less than 10 min from the time the sample is taken, the technician has a printout of the gradation. In several of our district laboratories, we dry fine aggregate samples by using microwave ovens that reduce the drying time to about one-third of that required when an electric oven is used. We have recently incorporated the pycnometer method for determining the material finer than the 0.075-mm (No. 200) sieve, which eliminates the necessity for drying the aggregate and saves considerable time.

At this point, the question probably arises, What return on investment can I expect from an efficient process control program? Our experience has demonstrated that the cost of this program ranges between $0.02 and $0.03/Mg ($0.018 and $0.027/ton). After recently reviewing the program, the chairman of the board of the Standard Slag Company stated that "quality control is the most economic insurance we can purchase."

If a quantity of aggregate is rejected because of failure to comply with the specified gradation after it is incorporated in a project, the aggregate producer could at least incur the cost of production, transportation to the project, placement, and removal. These costs could well exceed the selling price of the aggregate by five or more times. On the other hand, applying process control to one of our plants that produced a large riprap order last year resulted in our technicians handling and testing samples that weighed 2727 kg (6000 lb) or more, but also resulted in shipping more than 272 700 Mg (300 000 tons) of this material without a single rejection.

Additional savings result from having process control personnel perform other services within the organization, such as the following:

1. Testing of equipment performance, which would include analyzing the input and output of crushers to determine their effectiveness in size reduction and reduction of deleterious material to provide the necessary particles with one or more fractured faces and to produce the desired particle shape;
2. Analyzing material from prospective deposits;
3. Providing technicial service for customers; and
4. Management of air and water quality.

In summary, an effective process control program in a corporation must have at least the following essential elements:

1. The total backing of top management,
2. The cooperation of plant production personnel who should immediately report malfunctions in production or loading components since it is not possible for the materials technician to be at all points of production or loading at one time, and
3. Rapid sampling, testing, and reporting procedures to provide immediate feedback of test results to the plant superintendent so that when a process adjustment is necessary the superintendent can rapidly determine whether the adjustment produced the desired effect.

Publication of this paper sponsored by Committee on Quality Assurance and Acceptance Procedures.

Probabilistic Model of Aggregate Plant Production Systems

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Ping Kunawatsatit, Chulalongkorn University, Bangkok

A probabilistic model that could be used to evaluate the product characteristics of an aggregate processing plant was developed by combining several theories and mathematical models. The model interest was confined to crushing and screening subsystems. The final model is in the form of a computer programming model that is ready for application to similar plant systems. The computer model will store and compile a series of subroutines; each subroutine performs a specific function, and the whole model analysis procedure is controlled by a main program. A simulator is used to generate desired data to provide for the evaluation of the statistical nature of the output products. Through the use of the high-speed computer, parameters of plant production control—such as raw material feed rate, crusher settings, screen mesh sizes, combining and splitting of certain production flow streams, and appropriate production demand schedules—can be easily evaluated. By varying the data on raw feed material, the model evaluates the tonnage and gradation of the flow streams in the production plant as well as variability.

The program analyses used in the proposed model are logical and compatible with those used in the aggregate production industry. Extensive experimental data are still required to ensure the validity of the model.

The aggregate production industry is a growing industry. Through an evaluation of the present growth rate of aggregate consumption, it has been estimated that 1.76 billion Mg (1.9 billion tons) of crushed stone will be needed by 1986 (1). The increasing demand for construction aggregates will necessitate the design and development of new aggregate processing plants and the expansion of existing plants.

The study discussed in this paper was concerned with the analysis of crushed-stone plant production systems that include the crushing, screening, transporting, and storing of the material. Although the system as a whole looks simple, the processes themselves are very complicated. Of all the subsystems in the aggregate plant production system, crushing and screening are the most important and the most complicated ones. More attention has to be paid to these two subsystems since they not only control the production capacity of the plant but also affect such characteristics of the product as size distribution and shape.

It was the purpose of this study to evaluate several theories and mathematical models so as to develop a probabilistic model that could be used to evaluate the product characteristics of an aggregate processing plant. The model interest was confined to the crushing and screening subsystems. The final model is in the form of a computer programming model that is ready for application to similar plant systems. The computer model will store and compile a series of subroutines; each subroutine performs a specific function, and the whole model analysis procedure is controlled by a main program. A simulator is used to generate desired data to provide for the evaluation of the statistical nature of the output products.

CRUSHING MODEL

Early techniques for predicting crusher performance, which used the concept of mathematical models of comminution theories, were developed by Rittinger in 1867, Kick in 1885, and Bond in 1951. These "laws" were used to predict the energy spent in crushing or grinding material from one average size to another. All of these laws do not predict the output size distribution of crushers under given conditions, which is particularly important in aggregate plant production. This is especially critical when the subsequent process—either crushing or screening—is significantly affected by changes in feed particle size. Thus, the efficiency of the whole production system is intimately linked with the efficient interaction of the various subsystems. It is necessary to develop a crushing model that is capable of predicting the size distribution of plant flow streams and that thus enables the overall system to be optimized.

Several persons have developed methods for predicting the product size distribution of rock breakage. Broadbent and Callcott's approach for evaluating the crushing process (2) has been adapted in this study where the selection function P and the breakage function B are considered.

The selection function is said to be directly proportional to the particle size. The larger the feed particle is with respect to the crusher setting, the higher is the probability of breakage (3): $P_i = 1$ for all $x_i \geq \text{SET}$ and $P_i = k_o x_i$ for all $x_i < \text{SET}$ $(0 \leq P_i \leq 1)$, where P_i is the matrix element of the selection matrix P, which describes the probability that particle size x_i will break in the crushing process; k_o is a constant suggested by Guadin and Meloy (3) for given crushing conditions, and x_i is the feed particle size.

The breakage function $B(x_i, x_j)$ usually expresses a cumulative frequency distribution function, for which $B(x_i, x_j)$ is the mass fraction of crushed material between x_j and x_{j+1} where x_j is the product particle size. The breakage function is said to be characterized by the material and is easier to evaluate for crushing machines when expressed in terms of the dimensionless parameter x_j/x_i.

It is necessary to assume a mathematical form for the breakage function to make an analytical solution possible. Schuhmann's equation (4) is used in this study because of its simplicity and because it has been verified by other authors (5, 6). The Schuhmann equation can be expressed by

$$B(x_i, x_j) = (x_j/x_i)^N \tag{1}$$

Hence,

$$dB(x_i, x_j)/dx_j = N x_j^{N-1}/x_i^N \tag{2}$$

In terms of discrete form, the fraction of mass between size x_j and x_{j+1} is equal to

$$\Delta B(x_i, x_j) = (x_j/x_i)^N - (x_{j+1}/x_i)^N \tag{3}$$

The value of the modulus of distribution (N) has been found to be unity for brittle solids (7) and in the range of 0.90 to 0.95 for quartz (5). In the evaluation of limited crushing data in connection with this study, it was found that the average value of N is equal to 0.8 for a Pioneer roll crusher and 0.9 for a Telsmith 1.2-m (4-ft) standard cone crusher under certain given conditions.

SCREENING MODEL

The proposed screening model has been constructed around the probability of a particular size of particle passing through the screen opening. The probability of a particle size x_i passing through the screen openings has been found to be a function of the size of the particle and the size of the screen opening. If S is given as a screening matrix, its matrix elements can be expressed by

$$s_i = 1 - e^{-C[1 - (x_i/k_1 \text{CLOTH})]^R} \tag{4}$$

and, for $x_i \geq k_i^* \text{CLOTH}$, $s_i = 0$, where

s_i = probability of particle size x_i passing through the screen opening;
e = base of the Napierian logarithm, 2.718;
x_i = particle size;
CLOTH = size of the screen opening;
k_1 = a constant usually set equal to 0.875; and
C and R = constants that control the screening model and can be obtained through experimentation (if no data are available, values for C of 2.5 to 5.0 and values for R of 60 to 100 are reasonable assumptions).

ANALYSIS OF PLANT FLOW STREAM

The computer model evaluates the tonnage rate and gradation analysis of each stream of material in the flow diagram of the plant that is being analyzed (the model discussed in this paper is calibrated in U.S. customary

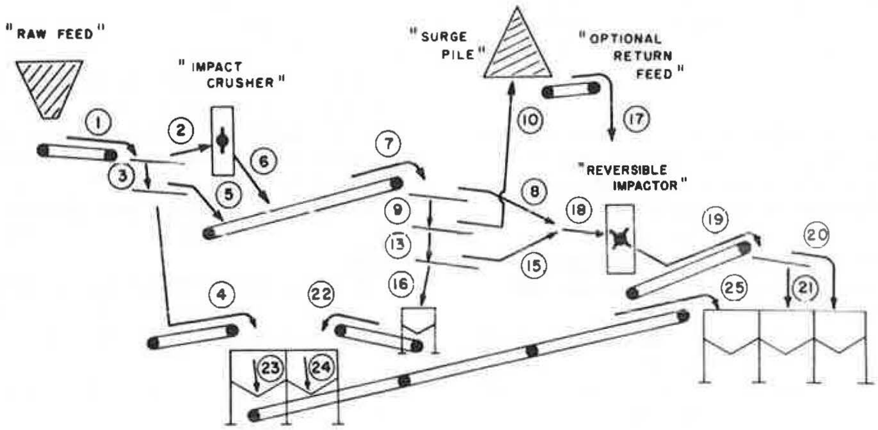

Figure 1. Flow-stream numbering system for sample aggregate plant.

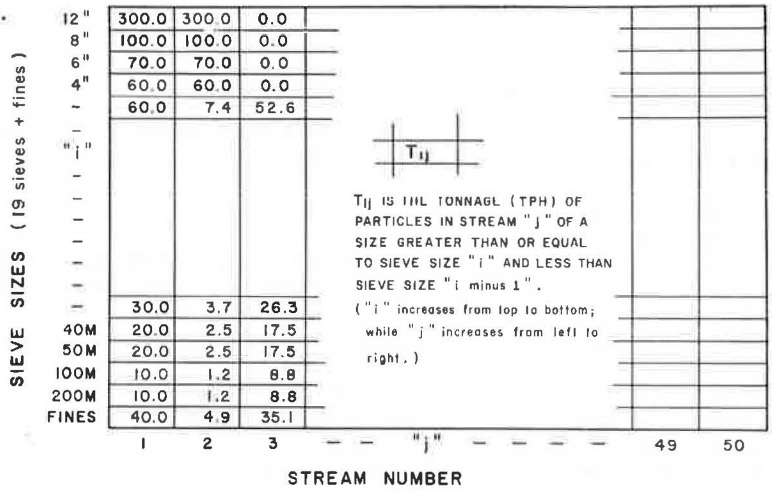

Figure 2. STREM array.

units of measurement). Therefore, the importance of carefully drawing and individually numbering the flow streams of the plant layout cannot be overemphasized. Each time the characteristics of a flow stream are changed by plant processing—for example, when the stream flows into a crusher, passes onto a screen, or combines with another stream—the old stream should be terminated and a new stream or streams, with new identification numbers, should be initiated. An example of this identification process is shown in Figure 1.

In addition to the plant flow diagram, it is necessary to identify the operating properties of each crusher and screen; these properties are essential information for the computer analysis and are identified when the crushing and screening subroutines of the program are called. The basic input data include the sieve sizes to be used to describe the product gradation, the size of the sieves in inches, the rate of raw feed flow into the plant, the gradation of the raw feed, and the estimated standard deviation of each feed size range.

Once the raw feed information has been read into the computer, the analysis of each flow stream in the plant model can be requested by calling the appropriate subroutine. As a basic rule, no stream can be called for analysis until all the streams that directly precede it have been analyzed. For instance, in Figure 1 neither stream 8 nor stream 9 can be determined unless the contents of stream 7 are known; likewise, stream 7 cannot be analyzed until streams 5 and 6 have been determined.

Flow-stream data are stored in a two-dimensional array called STREM, shown in Figure 2. Each column of the array contains the information for one stream. The array is currently set up to handle a maximum of 50 streams but could easily be expanded to handle more. Information will only be stored, of course, in the columns that correspond to the stream numbers included in the plant analysis.

Each row in the array corresponds to a different sieve size. The array is set up to handle 20 rows of information; the first 19 rows represent designated sieve sizes, and the last row represents all material finer than the nineteenth sieve. The designation of the different sieve sizes to be used for the gradation analyses is optional; however, since these sizes are used to establish the gradations of all streams in the plant, careful consideration should be given to their selection.

Each block in the STREM array represents the tonnage of material, for the stream represented by the column, that is contained between the sieve size designated by the row and the next larger sieve size. By using the information in this format, the percentage retained between sieves, the cumulative percentage retained on each sieve, plus the total stream tonnage can easily be calculated for each stream.

A similar array, ST, has been set up in the computer model to store the standard deviation of each sieve size of material for each flow stream being analyzed. This two-dimensional array is exactly the same size as the STREM array.

HONPI AGGREGATE PLANT PRODUCTION MODEL

A comprehensive aggregate plant production model developed in 1972 by Hancher (8)—set up as a computer model called HONDO—was developed to simulate the crushing and screening operations in aggregate plants. By giving certain characteristics of the feed material and the setup of plant facilities, the computer model evaluates the capacity and size distribution of any intermediate flow stream as well as the final end product in the plant flow system. However, no method was included to predict variation in plant processes.

The HONDO computer model consists of a series of subroutines, each of which simulates a certain type of operation in the plant. The total plant analysis is controlled by the main program, which dictates and directs the subroutine analyses to predict the quantities and size distributions of the required products. Regression models for both the crushing and screening models were set within the subroutines for specific types of equipment and were derived from the results of a compilation of various guidance and experimental data from machine manufacturers. The model has been deemed reasonably satisfactory for several analyses of aggregate-producing plants.

The proposed HONPI computer model has been developed by using existing theories for breakage and screening and the HONDO computer model. It has been directed toward the development of a simple and more practical method for predicting the performance of aggregate plant systems and expanded to a probabilistic prediction model. The probable prediction parameters for both crushing and screening were estimated on the basis of what was considered a reasonable extrapolation from a limited amount of available data, and a simulator function was used to generate random data for estimating the statistical nature of plant flow streams. The prob-

Figure 3. Essential subroutines of HONPI computer model.

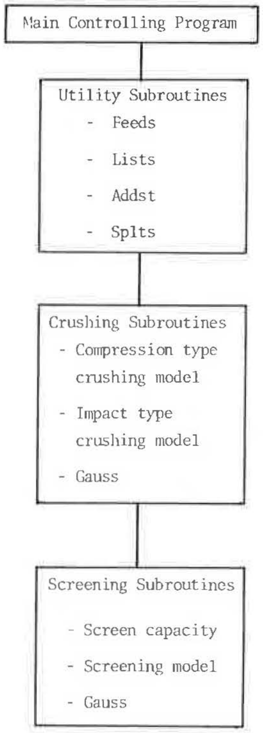

Table 1. Operating characteristics of Ward Stone Plant facilities.

Item	Operating Characteristics
Feed material	Limestone: 1613 kg/m³, dry quarried material, blocky particle shape
Primary crusher	76- by 106-cm jaw crusher (NTYPE = 1): 11.4-cm closed side setting, 227-Mg/h estimated capacity
Screen 1	1.5- by 3.6-m double-deck vibrating screen: 3.8-cm top deck of square woven wire mesh, 3.8-cm bottom deck of square woven wire mesh, 15° slope
Secondary crusher	1.2-m standard cone (NTYPE = 3): 3.8-cm closed side setting, 204-Mg/h estimated capacity
Screen 2	1.5- by 3.6-m triple-deck vibrating screen: 3-cm top deck of square woven wire mesh, 1.3-cm second deck of square woven wire mesh, 0.47-cm third deck of square woven wire mesh, 15° slope
Screen 3	1.5- by 3.6-m triple-deck vibrating screen: 5.7-cm top deck of square woven wire mesh, 3.8-cm second deck of square woven wire mesh, 1.3-cm third deck of square woven wire mesh, 15° slope
Tertiary crusher	76- by 106.6-cm roll (NTYPE = 2): 1.3-cm setting, 136-Mg/h estimated capacity 0.9-m short head cone (NTYPE = 3): 1.9-cm closed side setting, 136-Mg/h estimated capacity

Note: 1 kg/m³ = 0.062 lb/ft³; 1 cm = 0.39 in; 1 Mg = 1.1 tons; 1 m = 3.3 ft.

Figure 4. Flow diagram of plant operation.

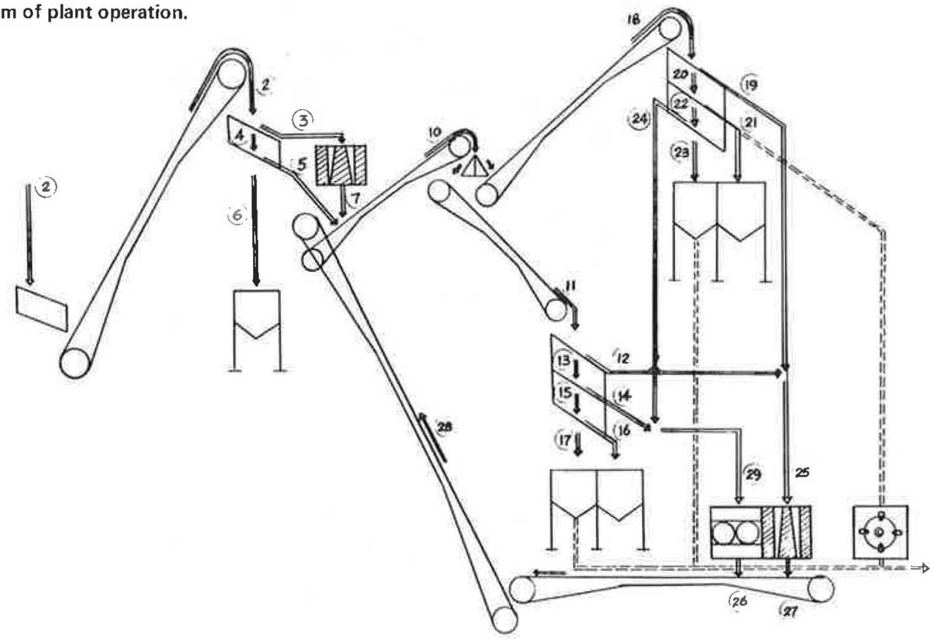

Figure 5. Basic input data for analysis of Ward Stone plant.

```
4 1/2  4  3 1/2  3  2 1/2  2  1 1/2  1 3/4  1/2  3/8  4M  8M  16M  40M  50M  80M 100 200
```

Elements of the Matrix "SIEVE" (19A4)

```
4.5  4.0  3.5  3.0  2.5  2.0  1.5  1.0  .75  .50  .375  .18709380469017401170070005900029
```

Elements of the Matrix "SIZES" (19F4.4)

```
200.17.227.144.654.364.372.678.586.690.092.994.396.697.998.599.5100.100.100.100.
```

TPH
(F4.4)

Cumulative Percent Retained on Each Sieve Size (19F4.4)

```
6.805.984.123.945.484.471.612.082.051.190.750.740.630.240.000.000.000.000.00
```

Standard Deviation of Cum. Percent Retained on Each Sieve (19F4.4)

Figure 6. Computer setup for plant analysis.

```
      PROGRAM HONPI(INPUT,OUTPUT,TAPE2=INPUT,TAPE3=OUTPUT)
      INTEGER CARD,PRINT
      COMMON STREM(20,60),WORK1(20),WORK2(20),SIZES(19),
     -                      SIEVE(19), CARD, PRINT
      COMMON ST(20,60)
      COMMON STEM(20,60)
      COMMON PCT(20,60)
      COMMON STMAX(20,60),STMIN(20,60)
      COMMON V(20,60),CON95(20,60)
      CARD=2
      PRINT=3
      READ(CARD,10) SIEVE
10    FORMAT(19A4)
      READ(CARD,20) SIZES
20    FORMAT(19F4.4)
      DO 35 K=1,50
      DO 34 J=1,50
      ST(J,K)=0.0
34    STREM(J,K)=0.0
35    CONTINUE
      WRITE(PRINT,40)
40    FORMAT(10X,≠SIMULATION OF WARD STONE PLANT≠)
      CALL FEEDS(2)
      CALL SCAPY(60,12,1.5,15,1,2,3,4,1.0,1.0,1.0,1.0,1.0,CAPY)
      CALL SCREN(1,1.5,2,3,4,CAPY,70.0,4.0)
      CALL SCAPY(60,12,0.75,15,2,4,5,6,1.0,1.0,1.0,1.0,1.0,CAPY)
      CALL SCREN(2,0.75,4,5,6,CAPY,70.,4.5)
      CALL CRUSH(3,1.5,7,3,225.)
      CALL ADDST(5,7,8)
      CALL LISTS(8)
      NPASS=1
      DO 25 I=1,6
      WRITE(PRINT,100) NPASS
100   FORMAT(1H1,///,≠*****STARTING PASS NO. ≠,I1,≠THROUGH CLOSED-CIRCUI
     1T ANALYSES*****≠,///)
      CALL LISTS(8)
      CALL ADDST(8,28,10)
      CALL LISTS(28)
      CALL LISTS(10)
      CALL SPLTS(10,.50,11,18)
      CALL LISTS(11)
      CALL LISTS(18)
      CALL SCAPY(60,12,1.25,15,1,11,12,13,1.0,1.0,1.0,1.0,1.0,CAPY)
      CALL SCREN(1,1.25,11,12,13,CAPY,70.,3.0)
      CALL SCAPY(60,12,0.50,15,2,13,14,15,1.0,1.0,1.0,1.0,1.0,CAPY)
      CALL SCREN(2,0.50,13,14,15,CAPY,70.,3.0)
      CALL SCAPY(60,12,.187,15,3,15,16,17,1.0,1.0,1.0,1.0,1.0,CAPY)
      CALL SCREN(3,0.187,15,16,17,CAPY,70.,3.0)
      CALL SCAPY(60,12,2.25,15,1,18,19,20,1.0,1.0,1.0,1.0,1.0,CAPY)
      CALL SCREN(1,2.25,18,19,20,CAPY,70.,3.0)
      CALL SCAPY(60,12,1.50,15,2,20,21,22,1.0,1.0,1.0,1.0,1.0,CAPY)
      CALL SCREN(2,1.5,20,21,22,CAPY,70.,3.0)
      CALL SCAPY(60,12,0.50,15,3,22,24,23,1.0,1.0,1.0,1.0,1.0,CAPY)
      CALL SCREN(3,0.50,22,24,23,CAPY,70.,3.0)
      CALL ADDST(12,19,25)
      CALL LISTS(25)
      CALL CRUSH(25,0.75,27,3,150.)
      CALL ADDST(14,24,29)
      CALL LISTS(29)
      CALL CRUSH(29,0.50,26,2,150.)
      CALL ADDST(26,27,28)
      NPASS=NPASS+1
25    CONTINUE
      CALL LISTS(28)
C     THIS IS THE END OF THE ANALYSIS
      CALL EXIT
      STOP
      END
```

abilistic approach is considered here because it coincides with real operating situations in which the feed material and the output products are almost always fluctuating.

Figure 3 shows the essential subroutines of the HONPI computer model. The individual subroutines are described below.

Subroutines

FEEDS Subroutine

The FEEDS subroutine is used to read in the information about the raw feed material where the number of the feed stream in the plant flow system is specified. The input for raw feed material must consist of

Figure 7. Computer results of plant analysis.

```
          SIMULATION OF HARD STONE PLANT

FEED STREAM - READ FROM CARD

STREAM NUMBER  2       200.0 TONS PER HOUR
 41/2    4 31/2    3 21/2    2 11/2    1  3/4  1/2  3/8   4M   8M  16M  40M  50M  80M  100  200
 34.4 19.8 35.0 19.4 20.0 16.6 12.6 15.4  6.9  5.8  2.8  4.6  2.6  1.2  2.0  1.0  0.0  0.0  0.0  0.0 TPH
 17.2  9.9 17.5  9.7 10.0  8.3  6.3  7.7  3.4  2.9  1.4  2.3  1.3   .6  1.0   .5  0.0  0.0  0.0  0.0 PCT
 17.2 27.1 44.6 54.3 64.3 72.6 78.9 86.6 90.0 92.9 94.3 96.6 97.9 98.5 99.5100.0100.0100.0100.0100.0 CUM RETN
 82.8 72.9 55.4 45.7 35.7 27.4 21.1 13.4 10.0  7.1  5.7  3.4  2.1  1.5   .5   .0   .0   .0   .0   .0 CUM PASS
 6.80 5.98 4.12 3.94 5.48 4.47 1.61 2.08 2.05 1.19  .75  .74  .63  .44  .24 0.00 0.00 0.00 0.00-0.00STD.DEV.

STREAM NO.  2 SCREENED OVER 1.50 INCH CLOTH    60 INCHES BY  12 FEET
OVERSIZE TO STREAM  3 UNDERSIZE TO STREAM  4
DECK  1 CAPACITY   358.95 TPH - CARRYING   200.00 TPH - IS   55.72 PER CENT LOADED
DECK1OPERATING AT86.9PERCENT EFFICIENCY


STREAM NUMBER  3       169.4 TONS PER HOUR
 41/2    4 31/2    3 21/2    2 11/2    1  3/4  1/2  3/8   4M   8M  16M  40M  50M  80M  100  200
 35.2 20.8 34.8 21.6 19.2 16.7 11.7  7.4   .9   .7   .4  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0 TPH
 20.8 12.3 20.5 12.7 11.3  9.9  6.9  4.4   .6   .4   .2  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0 PCT
 20.8 33.1 53.6 66.3 77.7 67.5 94.4 98.8 99.4 99.8100.0100.0100.0100.0100.0100.0100.0100.0100.0100.0 CUM RETN
 79.2 66.9 46.4 33.7 22.3 12.5  5.6  1.2   .6   .2  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0 CUM PASS
 6.12 5.49 5.03 5.28 4.38 3.59 1.78  .42  .27  .11  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00STD.DEV.
  2.7  2.5  2.3  2.4  1.8  1.6   .8   .2   .1   .0   .0   .0   .0   .0   .0   .0   .0   .0   .0  .00CONF95
 33.3 43.1 61.2 75.8 85.2 94.8 97.5 99.5 99.8100.0100.0100.0100.0100.0100.0100.0100.0100.0100.0100.0MAX.PCT.RET.
  8.8 21.8 46.3 54.2 70.3 77.7 90.0 98.0 98.9 99.6100.0100.0100.0100.0100.0100.0100.0100.0100.0100.0MIN.PCT.RET.


STREAM NUMBER  4        30.6 TONS PER HOUR
 41/2    4 31/2    3 21/2    2 11/2    1  3/4  1/2  3/8   4M   8M  16M  40M  50M  80M  100  200
  0.0  0.0  0.0  0.0  0.0  0.0  0.0  7.4  5.5  4.3  2.5  4.4  2.2  1.4  1.9  1.0  0.0  0.0  0.0  0.0 TPH
  0.0  0.0  0.0  0.0  0.0  0.0  0.0 24.3 18.1 13.9  8.0 14.3  7.2  4.7  6.3  3.1  0.0  0.0  0.0  0.0 PCT
  0.0  0.0  0.0  0.0  0.0  0.0  0.0 24.3 42.3 56.3 64.3 78.7 85.8 90.6 96.9100.0100.0100.0100.0100.0 CUM RETN
100.0100.0100.0100.0100.0100.0100.0 75.7 57.7 43.7 35.7 21.3 14.2  9.4  3.1   .0   .0   .0   .0   .0 CUM PASS
 0.00 0.00 0.00 0.00 0.00 0.00 0.00 5.32 7.60 7.93 8.18 5.56 4.53 2.24  .53  .00  .00  .00  .00  .00STD.DEV.
  0.0  0.0  0.0  0.0  0.0  0.0  0.0  2.4  3.4  3.5  3.7  2.5  2.0  1.0   .2   .0   .0   .0   .0  .00CNF95
  0.0  0.0  0.0  0.0  0.0  0.0  0.0 34.2 58.7 66.4 79.9 87.4 93.1 94.0 97.7100.0100.0100.0100.0100.0MAX.PCT.RET.
  0.0  0.0  0.0  0.0  0.0  0.0  0.0 13.2 25.2 37.8 47.8 69.7 77.4 86.4 95.9100.0100.0100.0100.0100.0MIN.PCT.RET.


STREAM NO.  4 SCREENED OVER  .75 INCH CLOTH    60 INCHES BY  12 FEET
OVERSIZE TO STREAM  5 UNDERSIZE TO STREAM  6
DECK  2 CAPACITY   269.91 TPH - CARRYING    30.64 TPH - IS   11.35 PER CENT LOADED
DECK2OPERATING AT65.0PERCENT EFFICIENCY


STREAM NUMBER  5        17.1 TONS PER HOUR
 41/2    4 31/2    3 21/2    2 11/2    1  3/4  1/2  3/8   4M   8M  16M  40M  50M  80M  100  200
  0.0  0.0  0.0  0.0  0.0  0.0  0.0  7.4  5.4  3.4   .9  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0 TPH
  0.0  0.0  0.0  0.0  0.0  0.0  0.0 43.5 31.4 19.6  5.5  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0 PCT
  0.0  0.0  0.0  0.0  0.0  0.0  0.0 43.5 74.9 94.5100.0100.0100.0100.0100.0100.0100.0100.0100.0100.0 CUM RETN
100.0100.0100.0100.0100.0100.0100.0 56.5 25.1  5.5   .0   .0   .0   .0   .0   .0   .0   .0   .0   .0 CUM PASS
 0.00 0.00 0.00 0.00 0.00 0.00 0.00 9.9510.04 3.64  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00STD.DEV.
  0.0  0.0  0.0  0.0  0.0  0.0  0.0  4.5  4.5  1.6   .0   .0   .0   .0   .0   .0   .0   .0   .0  .00CNF95
  0.0  0.0  0.0  0.0  0.0  0.0  0.0 64.4 95.7 99.4100.0100.0100.0100.0100.0100.0100.0100.0100.0100.0MAX.PCT.RET.
  0.0  0.0  0.0  0.0  0.0  0.0  0.0 30.3 57.4 88.9100.0100.0100.0100.0100.0100.0100.0100.0100.0100.0MIN.PCT.RET.


STREAM NUMBER  6        13.5 TONS PER HOUR
 41/2    4 31/2    3 21/2    2 11/2    1  3/4  1/2  3/8   4M   8M  16M  40M  50M  80M  100  200
  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  1.1  1.6  4.2  2.5  1.3  1.8   .9   .0   .0   .0   .0 TPH
  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  8.4 11.7 31.0 18.7  9.9 13.4  6.8   .0   .0   .0   .0 PCT
  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  8.4 20.2 51.1 69.8 79.7 93.2100.0100.0100.0100.0100.0 CUM RETN
100.0100.0100.0100.0100.0100.0100.0100.0100.0 91.6 79.8 48.9 30.2 21.3  6.8   .0   .0   .0   .0  -.0 CUM PASS
 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 3.65 9.63 7.90 5.86 3.41 1.10  .00  .00  .00  .00  .00STD.DEV.
  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  1.6  4.3  3.6  2.6  1.5   .5   .0   .0   .0   .0  .00CNF95
  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0 15.2 41.0 63.3 80.0 85.1 95.0100.0100.0100.0100.0100.0MAX.PCT.RET.
  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0   .8  7.7 37.0 58.2 73.8 91.3100.0100.0100.0100.0100.0MIN.PCT.RET.

STREAM NO. 3CRUSHED AT 1.50INCH SETTING AND   PRODUCT FED TO STREAM NO. 7

STREAM NUMBER  7       169.4 TONS PER HOUR
 41/2    4 31/2    3 21/2    2 11/2    1  3/4  1/2  3/8   4M   8M  16M  40M  50M  80M  100  200
  0.0  0.0  0.0  0.0  0.0 30.6 20.4 42.9 19.5 19.0  9.5 13.8  6.8  3.4  2.2   .4   .3   .1   .2   .1 TPH
  0.0  0.0  0.0  0.0  0.0 18.1 12.1 25.3 11.5 11.2  5.6  8.1  4.0  2.0  1.3   .2   .2   .0   .1   .1 PCT
  0.0  0.0  0.0  0.0  0.0 18.1 30.1 55.5 67.0 78.2 83.8 92.0 96.0 98.0 99.3 99.6 99.8 99.8 99.9100.0 CUM RETN
100.0100.0100.0100.0100.0 81.9 69.9 44.5 33.0 21.8 16.2  8.0  4.0  2.0   .7   .4   .2   .2   .1  -.0 CUM PASS
 0.00 0.00 0.00 0.00 0.00 1.93 3.22 1.62 1.16  .74  .58  .29  .14  .07  .02  .02  .01  .01  .00  .00STD.DEV.
 0.00 0.00 0.00 0.00 0.00  .87 1.45  .73  .52  .33  .26  .13  .06  .03  .01  .01  .00  .00  .00 .000CNF95
  0.0  0.0  0.0  0.0  0.0 22.0 36.7 59.3 69.9 80.2 85.4 92.7 96.4 98.2 99.4 99.6 99.8 99.8 99.9100.0MAX PCT RET
  0.0  0.0  0.0  0.0  0.0 15.2 25.4 53.2 65.4 77.1 83.0 91.6 95.8 97.9 99.3 99.5 99.8 99.8 99.9100.0MIN PCT RET


ADDING STREAM  5 TO STREAM  7 PUTTING RESULT IN STREAM  8

STREAM NUMBER  8       186.5 TONS PER HOUR
 41/2    4 31/2    3 21/2    2 11/2    1  3/4  1/2  3/8   4M   8M  16M  40M  50M  80M  100  200
  0.0  0.0  0.0  0.0  0.0 30.6 20.4 50.4 24.9 22.4 10.5 13.5  6.8  3.4  2.2   .4   .3   .1   .2   .1 TPH
  0.0  0.0  0.0  0.0  0.0 16.4 11.0 27.0 13.3 12.0  5.6  7.4  3.7  1.8  1.2   .2   .2   .0   .1   .1 PCT
  0.0  0.0  0.0  0.0  0.0 16.4 27.4 54.4 67.7 79.7 85.3 92.7 96.4 98.2 99.4 99.6 99.8 99.8 99.9100.0 CUM RETN
100.0100.0100.0100.0100.0 83.6 72.6 45.6 32.3 20.3 14.7  7.3  3.6  1.8   .6   .4   .2   .2   .1  0.0 CUM PASS
 0.00 0.00 0.00 0.00 0.00 1.93 3.22 3.93 4.51 1.42  .41  .29  .14  .07  .02  .02  .01  .01  .00  .00STD.DEV.
```

Table 2. Comparison between analytical results and observed results.

Stream	Sieve Size[a] (mm)	Cumulative Percentage Retained					
		Observed		HONPI		HONDO	
		Mean	Standard Deviation	Mean	Standard Deviation	Mean	Standard Deviation
3	115	18.6	7.23	19.7	5.71	21.4	NA
	100	27.9	7.09	34.5	5.90	33.7	NA
	90	41.8	9.38	54.1	4.52	55.5	NA
	75	52.8	8.04	65.8	3.88	67.6	NA
	64	71.4	6.14	78.7	5.79	80.8	NA
	50	83.9	4.67	88.2	5.40	90.3	NA
	37.5	92.9	3.53	96.3	1.03	98.2	NA
	25	99.6	0.30	99.9	0.03	99.4	NA
	19	99.7	0.22	100.0	0.00	100.0	NA
	12.5	99.7	0.23	100.0	0.00	100.0	NA
	9.5	99.7	0.23	100.0	0.00	100.0	NA
	4.75	99.7	0.23	100.0	0.00	100.0	NA
	0.425	99.7	0.23	100.0	0.00	100.0	NA
7	37.5	21.8	7.10	28.5	3.05	40.5	NA
	25	54.0	9.47	54.8	2.12	67.0	NA
	19	67.1	8.92	66.2	1.59	77.5	NA
	12.5	77.1	7.16	77.5	1.06	85.8	NA
	9.5	81.6	5.93	83.1	0.79	89.0	NA
	4.75	88.7	3.76	91.6	0.39	92.5	NA
	0.425	95.7	2.63	95.8	0.20	93.9	NA

Note: NA = not available.

[a] Corresponding sieve sizes: 4.5, 4, 3.5, 3, 2.5, 2, 1.5, 1, 0.75, 0.5, and 0.375 in, no. 4, no. 40.

1. The estimated flow rate of the raw feed material in tons per hour,
2. The size distribution of the raw feed material in the specified particle size ranges, and
3. The estimated standard deviation of each particle size of the raw feed material.

LISTS Subroutine

The LISTS subroutine is used to list all necessary information on the flow rate and gradation, as well as the standard deviation, of any specified flow stream in the aggregate plant production system.

ADDST Subroutine

The ADDST subroutine is used when two flow streams are merged into a single stream or a portion of one stream combines with a portion of another stream in the aggregate plant system.

SPLITS Subroutine

The SPLTS subroutine is used when any flow stream in the aggregate plant system is split into two separate streams. This subroutine can be revised in case it splits into more than two separate streams.

SCAPY Subroutine

The SCAPY subroutine is used to estimate the capacity of a vibrating screen. Many factors are known to affect screen capacity; various estimated factors proposed by manufacturers of screening equipment have been summarized. The screen capacity that was used in this subroutine is based primarily on the formula for vibrating screen capacity presented by the Iowa Manufacturing Company (9); two more variables—E and M—were added. The formula for screen capacity is

$$\text{CAPY} = \text{AREA} \times B \times E \times S \times I \times M \times D \times O \times H \times G \times A \times L \times W \qquad (5)$$

where

CAPY = capacity of the vibrating screen deck, expressed as tons per hour of feed material that the screen can handle at the specified screening efficiency and under a certain set of conditions;
AREA = net effective screening area, equal to the width times length of the screen less the deck part and frames that reduce the opening of the screen;
B = basic capacity of the screen, usually expressed as tons per hour of feed material per square foot of square opening screen cloth for a material that weighs 100 lb/ft^3 with 25 percent oversize, 40 percent half size, 50 percent open area, and 90 percent efficiency;
E = efficiency factor;
S = particle shape factor;
I = screen slope or incline factor;
M = material factor;
D = deck factor;
O = oversize factor;
H = half size factor;
G = weight factor;
A = open area factor;
L = slotted opening factor; and
W = wet screening factor.

SCREN Subroutine

The SCREN subroutine analyzes by probability analysis the size separation where the feed stream to the screen is divided into two new streams; the oversize material is restrained by the screen opening and remains on the screen surface, and the amount of undersize material that passes through the screen opening is evaluated by stratification, selection, and probabilistic processes. The probability of a particular size of particle passing through the screen opening follows the formula previously proposed for the screening model. A simulator is used to generate 20 estimates of the feed stream, and these are averaged out to a final estimated stream before screening is evaluated.

CRUSH Subroutine

The CRUSH subroutine is used to predict the crushed product gradation when the feed gradation is known. This subroutine has been constructed by using the proposed crushing model described previously. The only parameter used in this subroutine is the value of N, which is the distribution modulus according to Schuhmann's equation (4). The value of N will vary according to the type of crushing machine used. The result of evaluation of the available plant data is an estimated average value of N for Telsmith's 1.2-m (4-ft) standard cone crusher of 0.9 and 0.8 for a Pioneer roll crusher. The value of N is set equal to 1.0 for any compression type of crusher if no average value of N has been preevaluated. For the impact type of crushing machine, for which speed is the controlling criterion for required product gradation, the setting equivalent used is based on tables from the Iowa Manufacturing Company. A simulator is used to generate 20 estimates of the feed stream, and these are averaged out to a final estimated stream before crushing is evaluated.

Sample Analysis of Plant Production

To demonstrate the use of the HONPI computer model to evaluate plant production, a sample analysis is done for part of the Ward Stone Plant. A flow diagram of the plant operation is shown in Figure 4. The operating characteristics of the plant facilities are given in Table 1. The computer model set up for the plant is similar to the one proposed by Hancher (8). The basic input data for the feed to the plant are shown in Figure 5. Figure 6 shows the computer statement sequence required for the partial plant analysis. The results of the computer model analysis are shown in Figure 7.

Comparison between the proposed model (HONPI) and the existing model (HONDO) predictions for test samples collected at the plant has shown a certain degree of improvement of the HONPI model for aggregate plant analysis. Table 2 gives the results of the prediction of flow stream 7—the crushed product from a Telsmith 1.2-m (4-ft) standard cone crusher—and flow stream 3—the oversize material from the second deck of the first screen unit. Considerably more testing is required to evaluate the true capabilities of the model.

SUMMARY AND CONCLUSIONS

The primary objective of this research study was to develop a probabilistic prediction model for aggregate production plants. Through the use of available crushing and screening theories, Hancher's computer model (8) has been revised, and statistical devices have been added for the development of this proposed probabilistic model. Preliminary testing of the new proposed crushing and screening models has been confirmed by the manufacturer's recommended crushed product output and available screening data.

The probabilistic model proposed in this study will be a useful tool in the design and development of new aggregate plants as well as the expansion of existing plants. Although it does not purport to be a comprehensive model of the entire aggregate processing system, it does permit the user to seek, where appropriate, proper planning and optimization of his or her own design data for the data postulated in the basic model.

The analysis techniques used in the proposed model are compatible with those used in the aggregate industry in the United States. The use of such a model greatly facilitates the evaluation of many more plant arrangements, raw-feed compositions, and equipment settings than it is now possible to evaluate. It is also much easier, by using this model, to evaluate closed-circuit plant analyses (introduction of such material was omitted from this paper because of considerations of length).

Extensive experimental data would be required to ensure the validity of this model; however, collection of such data was not feasible in this study because of a lack of funding. It is believed that, after additional study and development, satisfactory, proven probabilistic prediction models might emerge.

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Applicability of Conventional Test Methods and Material Specifications to Coal-Associated Waste Aggregates

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The applicability of standard test procedures and specifications to nonconventional, coal-associated materials such as bottom ash, boiler slag, and coal mine refuse is evaluated. Test procedures for specific gravity, Los Angeles abrasion, degradation resistance, soundness, deleterious materials, weak particles, and leachate quality were performed. Asphaltic mixtures were analyzed for Marshall stability and flow, density, voids, and degradation. It was found that, because of the unique characteristics of bottom ash, boiler slag, and coal mine refuse, application of conventional test methods and specifications is often inappropriate and that effective use of such materials requires the development of new test methods or modifications to existing methods and specifications. Application of existing test methods and specifications may result in

the acceptance of a questionable material or arbitrary rejection of an acceptable material.

Natural aggregates such as crushed rock, sands, and gravels have been used in highway construction for many years. Based on extensive laboratory and field experience, a variety of test methods, specifications, and design and construction procedures have been developed to ensure that they provide adequate performance. In recent years, there has been considerable interest in the use of synthetic aggregates and waste materials, and it has been pointed out by several authors that these "new" materials exhibit properties and behavior that may be quite different from that of conventional aggregates (1,2,3).

Several approaches can be taken to test methods and specifications for these new materials:

1. They can be specified by applying the existing test methods and specifications and rejecting those materials that do not meet existing criteria.
2. Existing test methods and specifications can be modified to accommodate the new materials.
3. The unique properties of these new materials can be recognized and, where necessary, new test methods and specifications and design and construction procedures can be developed.

Research on coal-associated wastes has shown that the first approach given above is often inappropriate. Existing test methods and specifications developed for conventional aggregates often fall short of properly characterizing and evaluating coal-associated wastes. Adoption of standard test methods and specifications can lead to the acceptance of a questionable material or the arbitrary rejection of a suitable material. This implies that the second and third approaches are often more realistic for new materials such as coal-associated wastes.

In this paper, the applicability of selected test methods to coal-associated wastes is discussed in relation to the use of these materials in bituminous mixtures. Although the discussion in the paper applies to coal-associated wastes, similar problems may be encountered with other new materials such as incinerator residue, pyrolysis residue, various industrial slags, and recycled pavement materials.

MATERIALS

For the purposes of this paper, coal-associated wastes are defined as the solid wastes that arise from the mining, preparation, or burning of coal. Included in this definition are coal mine refuse, fly ash, bottom ash, and boiler slag (2,4). To understand properly the nature and behavior of these materials, it is important to know how they are produced and subsequently handled. Factors such as coal source, plant production operations, and disposal practices exert a significant influence on material properties and behavior (2).

Power plant ashes are produced by burning coal at high temperatures in steam-generating boilers or furnaces. The finer portion of the ash residue that is carried up the stack by combustion gases is called fly ash, and the coarser portion of the ash that is rejected by the stack is called bottom ash (4). The bottom ash from "dry bottom" boilers that burn pulverized coal over open grates is called dry bottom ash, bottom ash, or cinders. The ash produced by "wet bottom" boilers is called wet bottom boiler slag or boiler slag. Whereas dry bottom ash solidifies before it drops from the furnace, boiler slag is tapped from the furnace as a molten slag and dropped into water where it is quenched to an angular, glasslike material. Dry bottom ash is typically well graded and may contain varying quantities of popcornlike particles, which are loosely sintered agglomerates of coarse fly ash. The individual particles are vesicular and irregularly shaped and have a rough, gritty texture. Boiler slag, in contrast, is one-sized [predominantly 4.75- to 1.18-mm (no. 4 to no. 16) mesh], smooth-textured, and angular. Some vesicularity may be present, particularly in the coarser sizes (2).

Coal mine refuse represents the rejected rock, carbonaceous and pyritic shales and slates, waste coal, and other impurities produced during mine development and operation and during the coal-cleaning process. The refuse is generally composed of dark grey, flat, angular, shalelike particles graded from 80 to 50 mm (3 to 2 in) to 0.075-mm (no. 200) mesh. Poor resistance to weathering—i.e., slaking—is also a prominent characteristic of coal mine refuse (5). Coal washings, or slurries, are typically less than 1 mm (0.04 in) and are not considered in this paper.

A description of the study materials is given in Tables 1 and 2. The materials were selected to represent typical bituminous coal sources, production operations, and disposal practices in the Appalachian region. Tests were performed on these materials in strict accordance with the standard American Society of Testing and Materials (ASTM) procedures to (a) evaluate the suitability of the test methods and (b) observe the behavior of the material during the testing procedures.

AGGREGATE TESTS

Specific Gravity

Hubbard and Jackson (6) discussed the early definitions and test methods for specific gravity that have remained relatively unchanged for the past 40 years (7). The currently used saturated, surface-dry concept (ASTM C 127) has long been used for coarse aggregates (6), but it was found to be unsatisfactory for sands and so the present "cone method" (ASTM C 128) was developed (7). Various researchers have disagreed about the appropriateness of these tests, particularly as a measure of absorption (8, 9).

Representative specific gravity and absorption values for coal-associated wastes are given in Table 1. A comparison of specific gravity data for coal-associated wastes with those for conventional materials indicates that the ash particles, because of their vesicular nature, tend to be lighter in weight than natural aggregates. The fine fraction of BS material is an exception because it is dense and nonvesicular. In general, the coarser ash fractions have a lower specific gravity than the fine fractions because they are more vesicular. The high absorption obtained for the BA-1 coarse aggregate is caused by the presence of soft, friable agglomerates that become saturated when soaked. It was found that, when saturated, such particles may contain in excess of 30 percent moisture. It was also noted that, because the pores are large, the absorbed water drained off fairly quickly when the particles were removed from water. Therefore, the actual water that can be held in the pores may be considerably in excess of the 13.1 percent given in Table 1. In terms of determining the saturated, surface-dry condition, it is difficult to observe the disappearance of the surface sheen on both the irregularly textured bottom ash surface and the black glassy boiler slag particles.

Achieving a true saturated, surface-dry condition in the sand-size BA-1 and BA-2 particles also presents

Table 1. Properties of coal-associated wastes selected for study and ASTM test methods.

	ASTM C 127 and C 128				ASTM C 131, Los Angeles Abrasion					
Material	G_{bulk}	G_{app}[a]	Water Absorption (%)	ASTM C 88, Soundness Loss	Value	Grading	pH	$SO_4^=$ (mg/L)	ASTM C 123, Lightweight Particles[b]	ASTM C 142, Clay Lumps and Friable Particles (%)
BA-1										
Coarse[b]	1.549	1.942	13.1	16.6	50	D	9.2	49	67	7
Fine[c]	2.192	2.225	0.7	24.4					80	7
BA-2										
Coarse	2.164	2.266	2.1	6.3	38	B	3.8	375	14	0.2
Fine	2.417	2.468	0.8	9.8					25	0.2
BS										
Coarse	2.210	2.301	1.8	29.1	46	B	9.4	31	13	0.2
Fine	2.575	2.654	1.2	7.1					1	0.4
CMR-1										
Coarse	-	2.549[c]	-	68.9	37	A	7.5	1750	16	27
Fine									17	37
CRM-2										
Coarse	-	2.459[c]	-	82.7	26	B	7.9	725	9	70
Fine									18	76

Notes: 1 mg/L = 0.000 13 oz/gal.
Coarse = passing 50.8 mm (2 in) and retained on 4.75 mm (no. 4); fine = passing 4.75 mm (no. 4) and retained on pan.

[a] Apparent specific gravity. [b] Liquid specific gravity = 2.0. [c] ASTM D 854.

Table 2. Gradation of as-sampled materials.

	Percentage Passing Sieve Size[a]									
Material	50.8 mm	25.4 mm	12.7 mm	4.75 mm	2.36 mm	1.18 mm	0.60 mm	0.30 mm	0.15 mm	0.075 mm
BA-1	100	100	98	90	79	65	50	35	19	7.0
BA-2	100	98	91	66	49	33	22	13	6	1.9
BS	100	98	90	71	38	9	3	2	1	0.4
CMR-1	100	86	61	35	23	13	9	6	4	3.2
CMR-2	100	78	46	7	-	2	-	1	-	0.3

[a] Corresponding U.S. sieve sizes: 2, 1, and 0.5 in and nos. 4, 8, 16, 30, 50, 100, and 200.

difficulties. The 25 tamps in the sand cone compacted the samples to a state in which, because of the rough, irregular surface texture, the particles would hold together without slumping despite a dry appearance. This effect, plus the draining of water from the larger pores, gives anomalously low values of water absorption. Therefore, the bulk specific gravity and absorption values given in Table 1 are suspect.

The values for specific gravity of solids reported in Table 1 for the samples of coal mine refuse (CMR-1 and CMR-2) were determined by the soils procedure (ASTM D854). Bulk specific gravity and percentage absorption determined by standard aggregate procedures were found to be inappropriate for these materials because of the slaking tendency of the refuse. The low values of specific gravity reflect the porous nature of the unslaked particles and the presence of lightweight coal pieces.

Los Angeles Abrasion

The Los Angeles Abrasion test procedure (10) was devised by the city of Los Angeles in 1916 and subsequently adopted by the California Division of Highways. The specification limits (40 to 50) have changed little from those originally suggested in the late 1930s. The percentage of "wear" is considered to be an indicator of overall aggregate quality and is associated with mechanical strength and degradation during construction and service.

Values for percentage of wear for BA-1, BA-2, BS, CMR-1, and CMR-2 are given in Table 1. The test value reported for BA-1 is quite high and reflects the presence of a degradable "popcorn" type of material. On the other hand, BA-2 shows better toughness as indicated by the lower percentage value. BS has an intermediate percentage of wear.

The fines produced from the bottom ash and the boiler slag were intermediate in size and appeared as small, broken pieces of the larger particles with sharp edges and porous surfaces. This implied that the mechanism of degradation in the ash materials was primarily a fracturing process. In contrast, the fine material produced from the coal mine refuse was much finer and typical of abrasion or wearing action. This was verified by the rounded and smooth appearance of the refuse particles at the end of the test.

At the end of the test, it was possible to identify in the BA-1 material some popcorn particles that could be easily crushed between one's fingers. Two mechanisms are believed to contribute to this anomalous behavior. The first is a possible "cushioning effect" that results from degraded material and the relatively large volume of the test specimen that results from batching the lightweight bottom ash on a weight basis. A second mechanism may be the lower inertia of the lightweight particles, which causes them to roll more slowly to the bottom of the drum during the test.

The coarse fraction of the bottom ash and boiler slag is more vesicular than the fine fraction, and vesicularity affects strength. Therefore, the Los Angeles values obtained on the coarse fraction are not representative of the composite sample. This is especially true for the boiler slags. Although the standard Los Angeles test does not break down all the popcorn particles and in that sense is a mild test, it is perhaps too severe for the denser slaglike particles that degrade by fracturing (11). A modification of the test is needed—a reduced sample size adjusted for volume to account for the popcorn particles and fewer revolutions or lighter balls to account for the fracturing.

Because of its tendency to slake, the degradation of the coal mine refuse is much more pronounced in the presence of moisture than when it is dry. Thus, the standard Los Angeles abrasion test performed on a dry refuse will give a poor indication of the level of degradation that might occur under moist conditions in the field during construction or in service.

Figure 1. Gradations produced by degradation of mixture BA-1 by modified Los Angeles, mortar and pestle, and kneading compaction procedures.

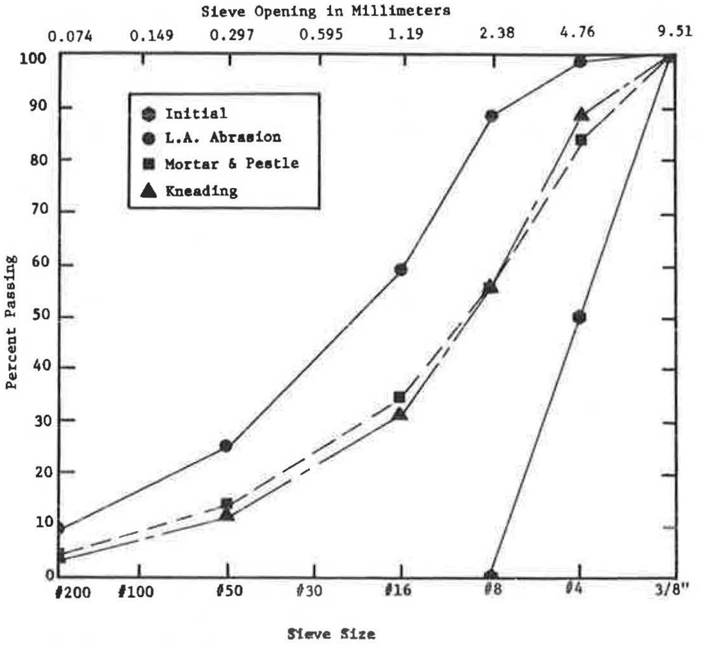
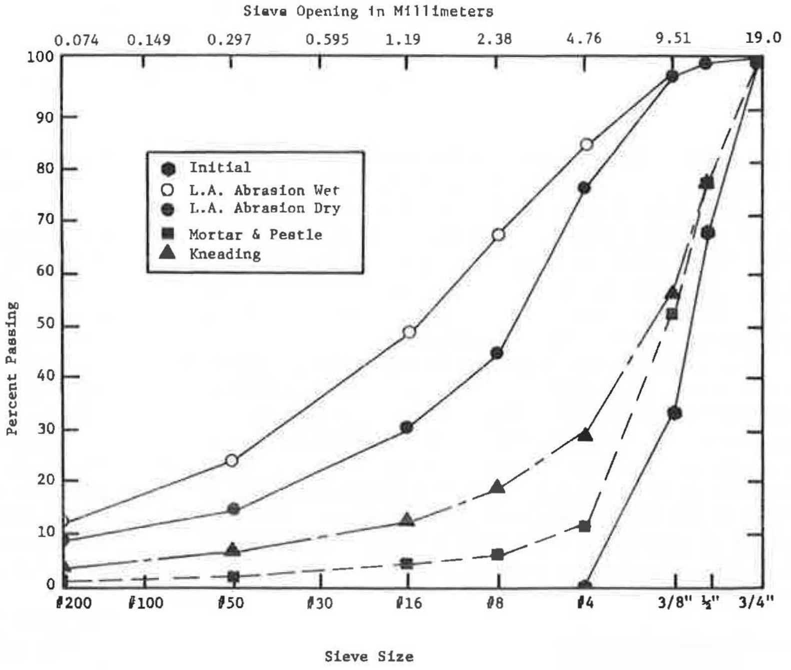


Figure 2. Gradations produced by degradation of mixture CMR-2 by modified Los Angeles, mortar and pestle, and kneading compaction procedures.



Nonstandard Degradation

The degradation characteristics of bottom ash, boiler slag, and coal mine refuse were studied by using three different testing procedures, performed both wet and dry: (a) a modified Los Angeles abrasion test, (b) a mortar and pestle test, and (c) a kneading compactor test. The test procedures, which are described elsewhere (12), were chosen to demonstrate different mechanisms of degradation. The Los Angeles test was modified by adjusting the weight of the specimen based on apparent specific gravity to give a constant sample volume. A washed sieve analysis and Atterberg limits test were performed at the end of each test. The mortar and pestle test was performed with 75 hand strokes of a rubber-tipped pestle for each 15- to 20-g portion of a 200- to 250-g sample. This level of effort was just sufficient to crush the friable popcorn particles in the BA-1 material. The kneading compaction was performed on a dry sample sandwiched between two 0.64-cm (0.25-in) rubber discs in a 10-cm (4-in) diameter mold by using 150 blows at a pressure of 3.45 MPa (500 lbf/in^2). The same gradation was used for each test but was chosen for each material to be representative of the as-produced materials.

The results of the degradation testing on the BA-1 material are shown in Figure 1. The modified Los Angeles test produced much severer degradation than the mortar and pestle and kneading compactor procedures. Although the level of degradation produced by the kneading and the mortar and pestle are very similar, the nature of the degradation is quite different. After testing, samples from the kneading and the modified Los Angeles abrasion tests contained soft and friable particles that could be crushed either by one's fingers or by the mortar and pestle. The fines produced in the Los Angeles and kneading tests included some of the crushed popcorn agglomerates as well as fractured corners from the more dense, slaglike particles. The fines produced by the mortar and pestle test contained mostly broken popcorn agglomerates.

Th mortar and pestle test adequately identifies the popcorn and highly vesicular friable particles. The Los Angeles and kneading tests reflect both fracture of corners from the denser, slaglike particles and the breaking of friable popcorn particles. As in the case of refuse, surface wear is not present because of the hard and brittle nature of the glass that comprises the ash. For bottom ash and boiler slag, the Los Angeles test is considered too severe to represent degradation as it might occur in the field because of the nature of the degradation mechanisms, the single-size gradation of the test sample, and the lack of confinement in the test. This is also true of the kneading test performed on a sample with a one-size gradation except that confinement is provided in the mold. Wet (versus dry) degradation had little effect on the bottom ash and boiler slag materials.

The results of degradation testing for CMR-2 material, including the modified Los Angeles abrasion test performed wet, are shown in Figure 2. Significant surface wearing of the refuse in the dry test is evident in the percentage of minus 0.075-mm (no. 200) mesh material produced and in the rounded appearance of the coarser particles. The wet degradation is significantly higher, principally because of slaking. The mortar and pestle is relatively ineffective in degrading the refuse. The Los Angeles abrasion test may be more representative of field degradation, but the quantity of water added to the specimen must be representative of field conditions.

Degradation in bottom ashes and refuse can also obscure the results of some of the other standard tests. One such test is the wet sieve analysis (ASTM C 117) in which constant degradation of the particles under rigorous agitation complicates the establishment of a termination point for the test.

Soundness

The use of salt crystallization tests to evaluate soundness dates back to 1826 when Brandt devised a test procedure in France that used a sodium sulfate solution (13). Sulfate tests of soundness have remained controversial over the years, particularly in relation to bituminous construction (14). The sulfate tests have been considered relatively ineffective for synthetic lightweight aggregates because of the presence of large pores in the coarse aggregate particles (15).

A summary of sodium sulfate soundness losses (ASTM C 88) is given in Table 1. The BA-1 material shows significantly higher losses than the BA-2 material. This is attributed to the presence of the highly porous and weak BA-1 popcorn particles, which disintegrate not only as a result of the expansive forces of the salt crystals but also as a result of rigorous shaking in the sieves after the soaking and drying cycles. In a comparison of the soundness losses for BA-1 and BA-2 materials with the associated absorption data, the more absorptive coarse particles exhibit a smaller loss of soundness. This reverse effect is caused by the drainage of the salt solution from the larger voids in the coarse particles. In fact, some of the coarse BA-1 particles that could be broken with the fingers still remained at the end of the soundness test.

The BS material behaved in the opposite manner: The coarser, more porous particles exhibited the greater loss of soundness. The voids in the coarse BS material are smaller than those in the BA-1 and BA-2 materials so that the salt solution was retained before drying. The coarser fraction of BS, which is necessary to make up the standard gradation for performing the test, is not representative of the larger portion [minus 4.76 mm (no. 4)] of the boiler slag, and its inclusion gives an anomalously high soundness value for the composite sample. For heterogeneous materials, the soundness or Los Angeles abrasion test samples must be representative of the grading of the material as it will be used if the test data are to be representative of the tested material.

The coal mine refuse exhibited very large soundness losses (Table 1). The severity of the standard sulfate soundness test on shale materials has been recognized by Shamburger, Patrick, and Lutton (16). This is caused in part by the slaking that occurs during wetting and drying, which overshadows the expansive forces produced by salt crystallization. Splitting along the bedding planes and complete disintegration into a fine powder were observed in the unsound particles of the refuse specimens.

Deleterious Materials

Various materials have been found to have an adverse effect on the performance of paving mixtures. Most of the literature that deals with deleterious materials emphasizes the effect of unsound and weak particles on the durability of portland cement concrete: e.g., soft and friable particles; clay lumps; coal and lignite (17, 18); chert and porous, absorbent sandstones (19, 20); and surface coatings (21). Thin and elongated pieces, vegetation, shale, soft particles, clay lumps, and clay coatings have been cited as objectionable substances in aggregates in bituminous mixtures (23). A number of different procedures for determining deleterious materials in aggregates are described in the literature (17, 18, 19, 20, 22). Currently, a wide variety of deleterious materials are covered in the material specifications.

Lightweight Particles

The results of an evaluation for clay lumps and friable particles (ASTM C 123 and C 146) are presented in Table 1. Because of its nonvesicularity, the fine fraction of the boiler slag contains few lightweight particles in contrast to its coarse fraction and ashes BA-1 and BA-2. The coal mine refuse contains relatively high percentages of lightweight particles—mostly coal fragments.

A visual examination of the particles that floated on the heavy liquid indicated that the major factor that affects the test results is particle vesicularity. Most of the popcorn particles in BA-1 material were floaters. Although the majority of the bottom ash particles that floated were vesicular and lightweight, not all of these particles were necessarily weak. A good portion of the refuse particles that floated were coal pieces, but appreciable quantities of shale pieces, which comprise the bulk of the material, also floated. No appreciable slaking was evident in the refuse specimen when it was agitated in the heavy liquid but, when it was brought in contact with water after testing, slaking occurred. The portions of the refuse that sank to the bottom were completely shalelike, but these pieces displayed as much slaking as the shale particles that floated. Although the test of lightweight particles is used to identify shale in conventional aggregates, the usefulness of this test on coal mine refuse, which is almost entirely composed of a carbonaceous shale, is open to question.

Weak Particles

The results of the tests for clay lumps and friable particles (Table 1) indicate that, although BA-2 material has minor quantities of soft, friable particles that can be crushed with the fingers, BA-1 material has appreciable amounts of such particles. The popcornlike agglomerates present in the BA-1 material showed little resistance to pressure applied with the fingers and disintegrated into individual grains of fly ash. The particles classified as friable in BS were thin and porous pieces. These pieces were brittle and could be easily broken between the fingers; however, this was not a disintegration phenomenon as in the case of bottom ashes. No clay lumps in the literal sense were encountered in any of the power plant aggregates tested.

The abnormally high percentages of clay lumps and friable particles reported for the coal mine refuse materials CMR-1 and CMR-2 reflect the slaking of these materials when they are soaked in water. The values given in Table 1 are arbitrary in that it was not possible to run the test on these materials in a meaningful manner because of continuous slaking and subsequent disintegration. In addition, most of the "nonfriable" pieces were coal fragments that had low resistance to breaking with the fingers but were still retained on the 0.075-mm (no. 200) sieve after washing.

The standard test procedure for clay lumps and friable particles (ASTM C 146) can be effectively performed on bottom ash and boiler slag. This test identifies the soft, popcornlike particles that are subject to degradation under compaction and traffic. Bottom ashes are free of clay lumps that can degrade into deleterious plastic fines, which suggests that higher percentages of friable particles than those customarily specified could be allowed in bottom ashes. However, excessive quantities of friable particles will undoubtedly hinder performance.

Leachate Tests

Although coal-associated wastes generally do not contain the types of deleterious materials that are found in conventional materials, in some instances they contain other deleterious elements that are potentially detrimental to their performance. For example, the presence of pyrites and other reactive salts in some of these materials can adversely affect pavement performance and may, in some extreme cases, be unacceptable from an environmental standpoint.

Table 1 gives pH values and the sulfate ($SO_4^=$) contents in milligrams per liter of water leachate. As previously reported by Anderson, Usmen, and Moulton (2), no direct correlation appears to exist between pH and sulfate content. All of the materials tested except BA-2 have leachates that are neutral or slightly alkaline in character. The acidic nature of the BA-2 leachate is attributable to the pyrite particles present in this material. The leachate water in this case was reddish-brown in color (iron oxide) and, on evaporation, left stains on the particle surfaces. The highest quantities of sulfate are observed in the CMR-1 and CMR-2 leachates. White salt crystals were seen on the particle surfaces of the refuse particles after the evaporation of the leachate water. Although they are not identified in Table 1, soluble salts other than sulfates are also present in ashes and refuse (2).

These considerations indicate that appropriate test methods and accompanying specification criteria designed to identify and exclude unacceptable material are definitely needed in the case of coal-associated wastes. A leachate analysis such as that reported in this paper and discussed by others (2, 12) should be considered if high pyrite contents are suspected. The sulfate content test suggested by Sherwood and Ryley (23) should also be considered.

INFLUENCE OF AGGREGATE PROPERTIES ON BITUMINOUS MIXTURES

The influence of the properties of bottom ash and boiler slag on bituminous mixtures was evaluated by Marshall mixture design procedures in which both Marshall (ASTM D 1559) and kneading compaction (ASTM D 1561) were used. The bottom ash was used at its as-sampled gradation (Table 2) but, based on earlier experience, the boiler slag was blended with a limestone sand to improve stability. Fly ash was added as a mineral filler, and an AC-20 asphalt cement was used in the mixture design. Gradations for the mixtures are given in Table 3.

Mixture Properties

Marshall stability and flow were measured in accordance with ASTM D 1560. Bulk specific gravity was determined by ASTM D 2726 by using saturated, surface-dry specimens, and the maximum specific gravity of the loose mixtures was determined by ASTM D 2041 by using the bowl method. Mixture properties are given in Table 3. The Marshall stability and flow values for mixtures prepared with BA-1, BA-2, and BS materials by using kneading compaction are shown in Figure 3.

The Marshall stabilities of the BA-1 and BA-2 materials peak at relatively high asphalt contents, which reflects the absorptive nature of the vesicular bottom ash particles. The BA-1 and BA-2 mixtures appeared extremely dry at lower asphalt contents because of incomplete particle coating. The BA-1 popcorn particles were difficult to coat except at high asphalt contents. This incomplete particle coating may account for the double peak in the Marshall stability curve of the BA-1 material (Figure 3), which is similar to the double peak encountered in the moisture density curve for clean sands. Bituminous mixtures of bottom ash generally yield low flow values, particularly at low asphalt contents, because of the irregular shape and gritty surface texture of the ash particles. More detailed discussions of the properties of bottom ash and boiler slag mixtures are given elsewhere (2, 12, 24, 25).

The specific gravities for the BA-1, BA-2, and BS mixtures are given in Table 4. The effective specific gravity is consistently greater than the apparent specific gravity. This is attributed to the difficulty in performing the tests for bulk specific gravity of the ash and the maximum specific gravity of the mixture. In the latter case, the difficulty is associated with the determination of the saturated, surface-dry condition on the "coated" (loose) mixtures, which absorb water during the test. It was observed that the large pores present in the coated particles allowed the drainage of water fairly quickly during the surface drying process. The effective specific gravity of the aggregate is calculated from the maximum specific gravity of the mixture, and any inconsistency in the effective specific gravity is

Table 3. Gradation of materials used in bituminous mixtures.

Material	Percentage Passing Sieve Size[a]								
	12.7 mm	9.5 mm	4.75 mm	2.36 mm	1.18 mm	0.60 mm	0.30 mm	0.15 mm	0.075 mm
BA-1	100	100	93	83	68	53	38	22	9
BA-2	100	91	74	56	39	28	18	11	6
BS	100	96	74	51	27	17	11	7	6

[a] Corresponding U.S. sieve sizes: 0.5 and 0.375 in and nos. 4, 8, 16, 30, 50, 100, and 200.

Figure 3. Marshall stability and flow curves for mixtures BA-1, BA-2, and BS.

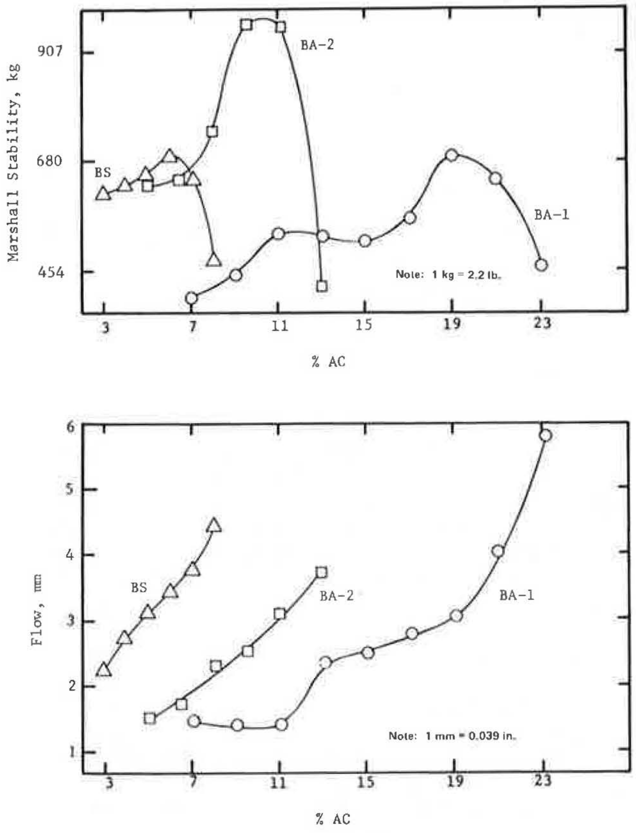


Table 4. Properties of bituminous mixtures that incorporate bottom ash and boiler slag.

Mixture	Aggregate			Mixture				
							R_r (%)[a]	
	G_{bulk}	G_{eff}	G_{app}	Asphalt (%)	Air (%)	VMA (%)	24-h Soak	Five Wet-Dry Cycles
BA-1	2.134	2.235	2.205	9.0	28.6	38.5	-	-
				11.0	-	-	89.2	-
				13.0	22.0	38.4	-	-
				17.0	15.7	39.0	-	-
				23.7[b]	-	-	100+	-[c]
BA-2	2.341	2.421	2.404	6.5	13.9	23.6	-	-
				8.0	10.5	23.3	-	-
				9.5	-	-	84.7	72.1
				11.0	4.7	23.7	-	-
				11.3[b]	-	-	95.7	-
BS	2.561	2.652	2.643	4.0	9.8	15.7	-	-
				5.0	7.1	15.3	-	-
				6.0	-	-	85.7	83.1
				6.9[b]	-	-	98.0	-
				7.0	2.4	15.4	-	-

[a] Percentage retained stability at 60°C (140°F).
[b] Optimum asphalt content (Marshall).
[c] Too weak to test.

reflected in the calculated air voids and voids in mineral aggregate. Further, any degradation that occurs during compaction opens new pores, and this alters both the bulk specific gravity of the aggregate and the maximum specific gravity of the mixture. Based on these observations, the validity of customary voids analyses and the standard test procedures are suspect relative to the more vesicular bottom ash and boiler slag mixtures.

Effect of Water on Marshall Stability

Two tests were performed to determine the effect of water on the stability of the mixtures. The first test was the immersion-Marshall test, and the second was a modified immersion-Marshall test in which the 24 h of soaking were replaced by five wet-dry cycles. Each cycle consisted of 12 h of soaking at 60°C (140°F) followed by 12 h of air drying at room temperature. The results of the tests, which are given in Table 4, were performed at "optimum" asphalt contents and lower asphalt contents that were considered economically compatible with conventional mixtures. Only the lower asphalt contents were used in the modified immersion-Marshall tests.

The index of stability retention (R_r) values given in Table 4 indicates that all of the mixtures tested exhibited satisfactory moisture-durability characteristics (75 percent stability retention was considered adequate). Although it is not shown, kneading compaction generally improves resistance to water because of a reduction in voids.

The more severe exposure conditions in the wet-dry cycles have resulted in a reduction of stability retention (Table 4). The most drastic reduction is observed in mixture BA-1. Although this mixture retained 100 percent of its stability in the 24-h soak of the immersion-Marshall test, it was weakened considerably on extended immersion and drying. The weakening was manifested as cracking of the specimens after the third cycle and complete deterioration in the subsequent cycles. Although such deterioration was not observed in the specimens of the other mixtures, some reddish-brown stains were visible on the surfaces of the specimens of mixture BA-2 along with a few pop-outs. The presence of reactive elements, such as pyrite and other soluble salts, clearly explains the behavior of the specimens of mixtures BA-2 in the immersion tests. Although staining may or may not be significant with respect to stability retention on immersion, the pop-outs are believed to be detrimental to mixture durability.

The 24-h soak immersion-Marshall test can be applied to the compacted bituminous mixtures that incorporate bottom ash and boiler slag without any technical difficulties. However, the duration of the exposure in this test may be too short to identify some of the potential problems associated with bottom ash. This test must be modified so that it can identify the reactivity or stripping problems properly. A wet-dry cycle test should be used as a guideline for developing a proper set of exposure conditions, and test methods such as those suggested by Schmidt (26) and Lottman and others (27) should also be considered.

Mixture Degradation

Because of the inherently low particle strength of bottom ash and boiler slag, considerable degradation takes place under both laboratory and field compaction (2). The degradation of bituminous mixtures that incorporate bottom ashes BA-1 and BA-2 and boiler slag BS under

Figure 4. Extracted gradations of bituminous mixtures BA-1 and BS after drop-hammer compaction.

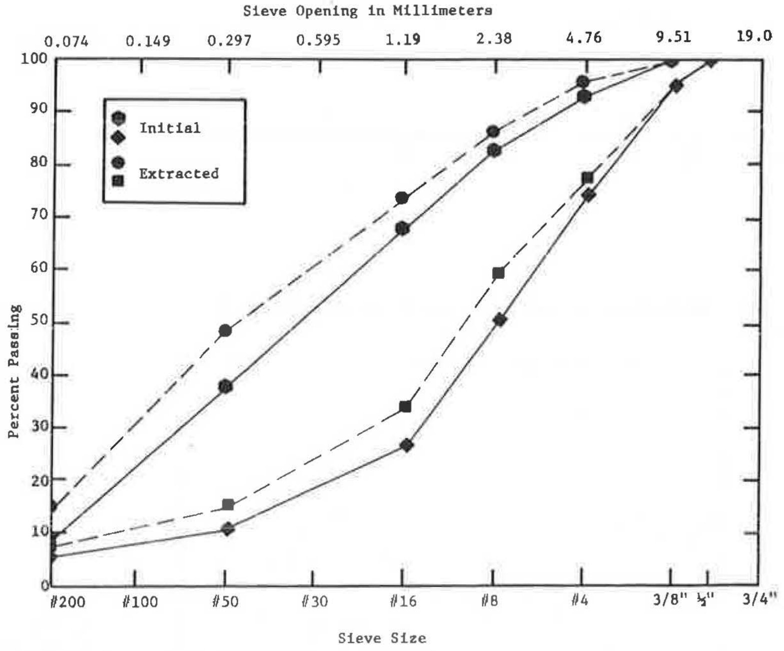


Table 5. Summary of applicability of conventional tests to coal-associated wastes.

Test Method	Bottom Ash	Boiler Slag	Coal Mine Refuse
Gradation			
ASTM C 136	A	A	A
ASTM C 117	NA	A	NA
Specific gravity			
ASTM C 127	NA	NA	NA
ASTM C 128	NA	Q	NA
Unit weight, ASTM C 29	A	A	A
Deleterious materials	I	I	I
ASTM C 123	Q	Q	Q
ASTM C 146	A	A	NA
Los Angeles abrasion, ASTM C 131	Q	Q	Q
Soundness, ASTM C 88	NA	Q	Q
Marshall method of mix design	NA	Q	-[a]
Bulk specific gravity, ASTM D 2726	A	A	-[a]
Marshall stability and flow, ASTM D 1560	A	A	-[a]
Maximum specific gravity, ASTM D 2041	NA	Q	-[a]

Note: A = applicable, NA = not applicable, Q = questionable applicability, and I = test results insufficient to characterize the material.

[a] Not studied.

drop-hammer and kneading compaction was studied by comparing the gradations of the mixture before and after compaction. Extraction tests were used to recover the aggregate. The results of the studies on mixtures BA-1 and BS in which drop-hammer compaction was used are shown in Figure 4. It was found that kneading compaction, which is not shown in the figure, results in slightly higher levels of degradation.

The degradation in the bituminous mixtures (Figure 4) is less severe than that in the previously discussed degradation tests performed on aggregate specimens (Figure 1). Some popcorn particles of the extracted BA-1 mixture did not experience excessive degradation during the laboratory compaction. Clearly, there is a potential for mechanical degradation in bottom ash and boiler slag, but a dense gradation and proper confinement will reduce this potential. As long as the stresses imposed by traffic do not break down the matrix of the mixture, the softer friable particles may escape degradation (2).

SUMMARY

A summary of the assessment of the applicability of selected conventional tests to three coal-associated wastes is given in Table 5. The surface texture and pore structure of bottom ash and boiler slag and the slaking of coal mine refuse complicate the determination of bulk specific gravity and absorption. The Los Angeles abrasion and sulfate soundness tests do not give a good indication of the mechanical integrity of the coal-associated wastes and fall short of representing the field conditions. The deleterious materials present in coal-associated wastes are not of the same origin and nature as those found in conventional materials and are thus not properly accounted for by the existing test methods and material specifications. The unit weight and dry sieve analysis are acceptable test procedures, but wet sieve analysis produces suspect test results because of degradation during sieving.

The unique properties of coal-associated wastes (i.e., pore structure and slaking) also obscure the test results on paving mixtures that incorporate these materials. An example of such a case is the voids analysis of bituminous mixtures prepared with power plant ashes. Existing methods of assessing moisture damage in bituminous mixtures are not sufficient to identify properly the potential problems associated with bottom ash. The degradation of the ash mixtures is also not properly evaluated by any of the current test methods.

CONCLUSIONS

Many of the existing test methods and associated specification criteria were not applicable to the three coal-associated wastes described in this paper, and modifications and additions to existing test methods and specification criteria are needed to enhance effective use of such materials. The considerations presented in this paper are not confined to coal-associated wastes but are pertinent to many other nonconventional materials. The specialized test methods and materials specifications developed for synthetic lightweight aggregates (28) illustrate this point. The following questions should be raised relative to the use of any new material in highway construction:

1. What are the physical and chemical properties of the product and what is its variability?
2. How do these properties affect design, construction, and performance?
3. How can the existing tests and specifications be used to assess properties and predict performance?
4. What modifications to the methods and criteria are needed?
5. What performance data are available as guidelines to modify or verify steps 1 through 4 above?

It should be clear from the information presented here that the assessment of new materials on the basis of conventional tests and specifications may lead to the approval of a questionable material or an arbitrary rejection of a suitable material. The experience and judgment of the materials engineer will be of increasing importance and value as new materials are proposed for use in highway construction.

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Implementation of Quality Assurance Specifications for Excavation and Embankment Construction in West Virginia

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Current West Virginia quality assurance specifications for excavation and embankment construction are the result of a research demonstration project that was constructed and evaluated in 1971 and 1972. The tests required of the contractor and their frequency and evaluation are described. The current specifications are not end-result specifications in that, rather than requiring that a total project be built and presented for acceptance, they require the contractor to present parts or segments of a project as lots for individual acceptance. They also require the contractor to perform his or her own quality control testing and allow the contractor to manage operations more efficiently. Acceptance by the West Virginia Department of Highways is based on the percentage of a lot that is within the specifications. Acceptance of individual lots can be based on departmental testing or on tests performed by the contractor. Lot-by-lot acceptance allows the reworking of individual lots to bring them within the specifications. All density testing by the contractor and the highway department is done by nuclear methods, and reporting is done on computer mark-sense forms.

The objective of the quality assurance specifications of the West Virginia Department of Highways is to provide realistic limits and tolerances that will ensure an acceptable level of quality in completed construction. This type of specification enables the contracting authority to estimate the percentage of material that is within specification tolerances. The acceptance procedures can be tailored to measure the uniformity of the material and produce a low risk of rejecting acceptable material or accepting substandard material.

SCOPE OF SPECIFICATIONS

If quality assurance specifications are to accomplish their purpose at the most appropriate level of construction, it is imperative that the contractor have an adequate quality control program. These specifications define the contractor's responsibility for the quality control of the product and its construction as well as the buyer's responsibility for acceptance testing. It is important that the contractor describe his or her method of quality control to ensure an adequate and acceptable level of quality by filing a quality control plan before the start of work. It is the intent of the specifications to allow the contractor as much leeway as possible so as not to restrict new methods and ideas. It is necessary, however, to specify a minimum of measurements and testing so that a realistic estimate of quality can be made.

The current West Virginia specifications, which are in the process of being implemented, require that the contractor control the quality of the unclassified excavation to be used to form the embankment and subgrade. This quality control includes the density, percentage of organic content, lift thickness, and, to a certain degree, placement of material. Although the specifications do not classify the material from the excavation into different pay items, the specifications do require that a certain quality of material be placed at designated locations, such as select embankment for drainage purposes, which consists of limestone or sandstone with a limit of 15 percent of other suitable random material. After the contractor has placed a "measured amount of specified material"—the definition for one lot of embankment or subgrade material—and has performed quality control tests, the lot is offered to the highway department for acceptance.

EXPERIMENTAL PROGRAM

Initial Research

Current quality assurance specifications for embankment and subgrade in West Virginia are based on experience and knowledge gained from research that included a demonstration construction project (1). The demonstration project accompanied the construction of RS-S-733(3), a two-lane, controlled-access connector between US-21 and I-77 in Kanawha County. Construction began on January 12, 1971.

The project was 3.38 km (2.1 miles) long and had 690 244 m^3 (902 805 yd^3) of unclassified excavation. The unclassified excavation consisted of A-2-4 to A-6 soil and bedrock of sandstone and various grades of shale. The project was completed and opened to traffic in November 1972, and the completed project carried all of the southern terminus traffic for I-77 for 2 years until the next segment of the Interstate was completed into Charleston, West Virginia.

Testing and Lot Size

The contractor elected to use both procedures of the American Association of State Highway and Transportation Officials (AASHTO) and materials procedures (MP) of the West Virginia Department of Highways, departmental forms, and a nuclear moisture-density gauge of the direct transmission type for testing. All test sites were selected on a random basis, and the contractor conducted approximately one test for each 1538 m^3 (2000 yd^3) of embankment and subgrade as specified by the contract documents. The lot size of embankment and subgrade material that the specifications suggested be used to present material to the highway department for acceptance was 2508 m^2 (3000 yd^2). The lot size could be increased if production were greater than 8360 m^2/d (10 000 yd^2/d). The contract documents approved for the research project allowed the department to select any lot size. As a result, highway department lot sizes did not always coincide with the contractor's lots. The lot sizes offered by the contractor actually varied from 670 to 6690 m^2 (800 to 8000 yd^2). The lot size selected by the department varied from 926 to 10 786 m^2 (1108 to 12 900 yd^2).

Contractor Quality Control

The contractor's quality control program for the re-

Table 1. Estimating the percentage of a lot within tolerance: positive values of Q_L.

Percentage Within Tolerance	Number of Tests			Percentage Within Tolerance	Number of Tests		
	Three	Four	Five		Three	Four	Five
99	0.60	0.66	0.66	78	0.47	0.38	0.33
98	0.60	0.64	0.65	77	0.46	0.36	0.32
97	0.60	0.63	0.62	76	0.44	0.35	0.30
96	0.60	0.62	0.60	75	0.43	0.34	0.29
95	0.60	0.60	0.58	74	0.41	0.32	0.28
94	0.59	0.59	0.57	73	0.40	0.31	0.27
93	0.59	0.58	0.55	72	0.39	0.30	0.25
92	0.59	0.56	0.53	71	0.37	0.28	0.24
91	0.58	0.55	0.51	70	0.36	0.27	0.23
90	0.58	0.54	0.50	69	0.34	0.26	0.22
89	0.57	0.52	0.48	68	0.32	0.24	0.21
88	0.56	0.51	0.46	67	0.31	0.23	0.19
87	0.55	0.50	0.45	66	0.29	0.21	0.18
86	0.54	0.48	0.44	65	0.27	0.20	0.17
85	0.54	0.47	0.42	64	0.26	0.19	0.16
84	0.53	0.46	0.41	63	0.24	0.17	0.15
83	0.52	0.44	0.40	62	0.22	0.16	0.14
82	0.51	0.43	0.38	61	0.20	0.15	0.13
81	0.50	0.42	0.37	60	0.19	0.13	0.11
80	0.49	0.40	0.36	55	0.09	0.07	0.06
79	0.48	0.39	0.34	50	0.00	0.00	0.00

Table 2. Estimating the percentage of a lot within tolerance: negative values of Q_L.

Percentage Within Tolerance	Number of Tests			Percentage Within Tolerance	Number of Tests		
	Three	Four	Five		Three	Four	Five
50	0.00	0.00	0.00	21	0.48	0.39	0.34
45	0.09	0.07	0.06	20	0.49	0.40	0.36
40	0.19	0.13	0.11	19	0.50	0.42	0.37
39	0.20	0.15	0.13	18	0.51	0.43	0.38
38	0.22	0.16	0.14	17	0.52	0.44	0.40
37	0.24	0.17	0.15	16	0.53	0.46	0.41
36	0.26	0.19	0.16	15	0.54	0.47	0.42
35	0.27	0.20	0.17	14	0.54	0.48	0.44
34	0.29	0.21	0.18	13	0.55	0.50	0.45
33	0.31	0.23	0.19	12	0.56	0.51	0.46
32	0.32	0.24	0.21	11	0.57	0.52	0.48
31	0.34	0.26	0.22	10	0.58	0.54	0.50
30	0.36	0.27	0.23	9	0.58	0.55	0.51
29	0.37	0.28	0.24	8	0.59	0.56	0.53
28	0.39	0.30	0.25	7	0.59	0.58	0.55
27	0.40	0.31	0.27	6	0.59	0.59	0.57
26	0.41	0.32	0.28	5	0.60	0.60	0.58
25	0.43	0.34	0.29	4	0.60	0.62	0.60
24	0.44	0.35	0.30	3	0.60	0.63	0.62
23	0.46	0.36	0.32	2	0.60	0.64	0.65
22	0.47	0.38	0.33	1	0.60	0.66	0.66

search project included responsibility for the design, adjustment, and control of his or her processes and all materials submitted to the highway department for acceptance. As part of the project requirement, it was necessary for the contractor to document his or her quality control system and submit it to the department for review and approval. The minimum requirements specified were that the contractor provide a quality control system that would provide reasonable assurance that all materials and products submitted to the department for acceptance conform to the contract requirements. This included sampling and testing methods, sampling frequency, types of forms, type of documentation of process control, and a procedure for reworking or disposing of nonconforming material. The initial documentation of the contractor's quality control system was very brief and, since this was a pioneer effort on the part of the contractor, as much assistance as possible was ultimately provided by the department to make the documents more responsive to project requirements. This was accomplished through questionnaires and orientation and training sessions. The orientation and training sessions were conducted for personnel of the contractor and the Federal Highway Administration and for project and district personnel of the West Virginia Department of Highways.

The contractor tested at the required frequency but did not in all cases record types of deficiencies or corrective action as required by the specifications. The contractor's quality control system detected three nonconforming lots that were reworked before the department was notified that the lots were ready for acceptance. The contractor did not evaluate the tests according to MP106.00.20—West Virginia Acceptance Plan "A" Method of Estimating Percentage of Material or Construction That Will Fall Within Specification Limits (2)—which consists of a set of tables that indicate the percentage of a lot within tolerance (Tables 1 and 2). The percentage within tolerance was determined by evaluating the dry density according to the following equation:

$$Q_L = (\bar{X} - L)/R \qquad (1)$$

where

Q_L = lower quality index,
$\bar{X}$ = average dry density of lot,
L = 0.95 (maximum T99 density) for embankment and 0.98 (maximum T99 density) for subgrade, and
R = range of dry densities in lot (highest minus lowest value).

Acceptance

The department's acceptance testing found one lot outside specification limits, and it was rejected. The specifications required that 80 percent of the lot have a target percentage of density of ≥95 percent for embankment and ≥98 percent for subgrade. The contractor's three tests for the rejected lot had a range of 160 kg/m^3 (10 lb/ft^3), a $\bar{X}$ of 1984 kg/m^3 (124 lb/ft^3), and a Q_L of 0.20. Even though all the tests passed, had the contractor evaluated them by MP106.00.20, he would have realized that areas of low density were probable and that the estimate within tolerance was 61 percent based on his minimal number of tests. The department's actual acceptance tests, which required five density tests within a lot, estimated that 63 percent was within tolerance. Highway department testing indicated a range of 304 kg/m^3 (19 lb/ft^3), a $\bar{X}$ of 1977 kg/m^3 (125 lb/ft^3), and a Q_L of 0.15 and actually had one test result within only 88 percent of the maximum density. Although the contractor's testing was minimal, the estimate of the percentage within tolerance was very close to the department's estimate. The two evaluations plus the one test with very low density indicate that the estimate is reasonable.

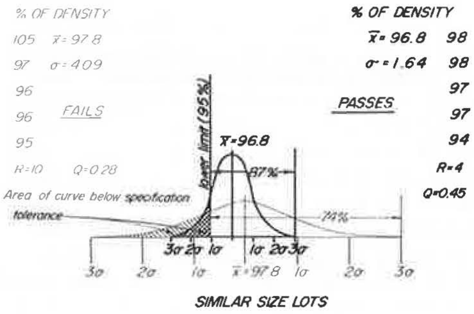
In accordance with the specifications, the department tested the reworked lot for acceptance. This was at the contractor's expense at a unit cost of $125/lot, which included five tests. After more compactive effort, the reworked lot met specifications. This failure occurred early in the progress of the project and, although the penalty was not excessive, it did cause the contractor to control the quality of density more carefully.

Evaluation of Demonstration Project

After completion of the research project, it was thoroughly evaluated. This evaluation found that the contractor's and department's personnel associated with this project demonstrated through the operation that the performance specifications are workable, equitable, and enforceable.

Conclusions from the research indicated that all concerned were benefited. The contractor benefited be-

Figure 1. Theoretical estimate of percentage within tolerance.



cause he was allowed better control of his work. The highway department benefited because this type of specification has the potential for producing more uniform compaction and allows much greater flexibility in the use of available inspecting forces. The statistically based acceptance plan, in conjunction with random sampling plans, provided a reasonably accurate estimate of the density for embankment and subgrade.

DEVELOPMENT OF CURRENT SPECIFICATIONS

As a result of these findings, it appeared to be feasible to use this type of specification for statewide control of density in the standard specifications. To adopt this type of specification on a statewide basis, it was necessary to consider whether variation in materials would affect the specifications.

The bedrock in West Virginia is composed almost entirely of sedimentary rock units that consist of shale, siltstone, sandstone, limestone, and coal; some of these units are slightly metamorphosed in the eastern part of the state. Shale is the predominant rock type in many areas. The topography is almost entirely mountainous. As a result, most projects of any size require large volumes of earthwork. The earthwork often contains many types of soil and a variety of types of bedrock. Because of this, the specifications for statewide control of density had to consider that the materials would vary considerably within a given project and could vary within a given lot. Therefore, instead of using the value for dry density to determine the quality index, it was necessary to use the percentage of density.

Determination of Percentage of a Lot Within Tolerance

The percentage of a lot that is within density tolerance, as determined by the formula in Equation 1, required a change because the material within a lot could vary. Although Equations 1 and 2 are essentially the same, the data used for the statistical values had to be changed because the maximum density required for an individual test within a lot of five tests might be different. Therefore, the following changes were made in regard to the data used in Equation 1:

$$Q_L = (\bar{X} - L)/R \qquad (2)$$

where

$\bar{X}$ = average percentage of dry density for the five tests,
L = lower tolerance limit in percentage or target percentage of dry density, and
R = range or difference between largest and smallest percentage of dry density.

Q_L is used to enter the tables in West Virginia Department of Highways MP106.00.20 to determine the percentage of the lot within tolerance. L is the percentage of density on which the decision of acceptance is based and is not to be confused with the percentage of density that the contractor may try to achieve to ensure that the lot has the minimum of 80 percent within tolerance. In Figure 1, two examples are shown in which the lots are of similar size. In this example, both lots have an average percentage of dry density ($\bar{X}$) above the target percentage of density. However, the range of the percentage of dry density (R) for the lot on the left is much greater than the range for the lot on the right. When Table 1 is entered with a Q_L value of 0.28 and five tests, it is found that only 74 percent of the lot on the left is estimated to have a percentage of the required maximum dry density of 95 percent or above. Thus, the lot fails because it does not meet the minimum of 80 percent within tolerance required in the specifications. After the calculations for Q_L are performed, an estimated 87 percent of the lot on the right side of Figure 1 is densified to a percentage of the required maximum dry density of 95 or greater. The illustration on the left in Figure 1 exemplifies that, when the percentage of density for tests within a lot have a large R and standard deviation (σ), it is possible for a relatively high percentage of the lot to be substandard even though all of the test results are above the target percentage of density. This normally indicates poor quality control of the densification of the lot. In contrast, the illustration on the right of the figure, which has a smaller R and σ, can tolerate a lower $\bar{X}$ and an actual test below the target percentage of dry density.

Other significant changes that resulted from evaluation of the research project are described below:

1. Lot size—In the research project, the contractor's lot size and the department's lot size were not always analogous and, further, the research project specifications often resulted in a lot size where the contractor had only one or two tests. In actuality, 63 percent of the lots offered to the highway department had three or fewer tests. Since the size of the lot has considerable influence on the financial risk to the contractor, a sublot size of 1910 m^3 (2500 yd^3) for embankment and 120 linear m (400 ft) for subgrade was selected and judged to be the best compromise for this evaluation. Each lot has at least five sublots of approximately equal dimensions. As a result of the experience gained from the research demonstration project, the lots presented to the department by the contractor are the same lots that are evaluated for acceptance.
2. Number of tests—Based on the research, at least five tests per lot were desirable to provide a reasonably accurate estimate of the percentage of dry density within tolerance for an individual lot. Because it was also desirable to have the option to use the contractor's quality control testing in the acceptance evaluation, it was necessary to revise the contractor's minimum testing. Thus, the contractor's quality control testing is to include at least one nuclear moisture-density measurement made at a random location in each sublot. The random locations are selected in accordance with MP712.27.26—Procedure for Determining Random Locations for Compaction Tests on Embankment, Subgrade and Base. For lots that consist of more than one lift, the contractor is to include testing on each lift.

Test Methods

Moisture Control

The lots of embankment and subgrade material are required (as in the research project) to be within the specified moisture tolerance of 4 percent below optimum to 3 percent above optimum. This tolerance was evaluated and adopted as a result of a study conducted before 1968. Moisture tolerance has proved to be a suitable control for most soil material found in West Virginia. The only exception is soil that has a high silt content. The specifications and procedures for this material require that moisture be controlled at optimum or below until pumping has been checked. This type of soil, however, is not commonly encountered in current construction in West Virginia. The percentage of moisture is determined in conjunction with density testing by using MP712.21.25 and MP300.01.01 and the nuclear gauge.

Density Testing

Soil that has less than 35 percent retained on the 19-mm (0.75-in) sieve is tested in accordance with the department's MP712.21.25—Nuclear Field Density Test for In-Place Density for Compacted Soils, Soft Shales, or Random Material Layers Having Less Than 35 Percent Retained on the [19-mm] ¾-Inch Sieve and Soil Cement Stabilization—which uses a direct-transmission type of nuclear gauge. No laboratory testing is normally required since a table of maximum density and optimum moisture values is used in conjunction with the one-point Proctor test to determine AASHTO T 99 optimum moisture and maximum density. Only one determination of optimum moisture and maximum density is required for individual lots in cases in which the material remains uniform.

For soil material that has 35 percent or more retained on the 19-mm (0.75-in) sieve, the research project found that very little of the material from the excavation could be tested by the highway department's roller pass procedure because of the nonuniform nature or the nominal particle size of the material. This procedure required that the material remain uniform and somewhat homogeneous. In addition, the method for determining the maximum density used in the research project was quite time consuming. Only one lot of 2470 m^2 (2950 yd^2), or less than 1 percent of the excavation, was tested.

Because of the excessive settlement observed in various areas of the state in many embankments formed of shale and lifts that contained combinations of soil and bedrock (3), it was decided to initiate and document control of compaction on these embankments. The nuclear testing equipment currently owned by the West Virginia Department of Highways has a maximum depth reading in the direct-transmission mode of 305 mm (12 in). The department allows loose lifts that vary from 200 to 610 mm (8 to 24 in) in placing shale. Since the quality of the shale can vary from soil to rocklike material, it was decided to adapt the specifications to this type of material instead of processing the material to accommodate methods of testing.

Two methods of compaction control are used for material (other than rock lifts) that has 35 percent or more retained on the 19-mm (0.75-in) sieve:

1. MP300.01.01—Method of Test for Quality Assurance of Compaction of Untreated and Stabilized Aggregate and Granular Embankment Material by Roller Pass Method—a new and less time-consuming roller pass test, is used for soil that is relatively uniform in gradation and is composed of particles of a nominal 254 mm (10 in) or less. The material is controlled to a target percentage of dry density of 95 percent. In part 1 of the materials procedure, the maximum density is developed in the field by the contractor's equipment by using a specified minimum compactive effort (roller weight) and a growth curve. The growth curve is evaluated after a specified number of passes have been conducted on the test section. The required maximum density is considered to be achieved when a minimum change of 32 kg/m^3 (2 lb/ft^3) or less occurs after two passes of the roller. The two passes normally evaluated are numbers 13 and 14. The method is normally used on subgrade material that is specified to be natural or synthetic mineral aggregate—e.g., broken or crushed rock, gravel, or slag that can be incorporated in a 200-mm (8-in) loose-depth lift. It may also be applicable to some embankment material.

2. Material that either has a nonuniform gradation or includes particles larger than a nominal 250-mm (10-in) top size or both is proof rolled by making two or more passes over the entire area at a speed of not more than 8 km/h (5 mph) with a 45-Mg (50-ton) roller. All unstable areas or soft spots that are disclosed are to be corrected before placement of overlying lifts.

Documentation of Results of Density Tests

All test results for MP712.21.25 and MP300.01.01 are recorded on computer mark-sense forms. This includes tests performed by the contractor and the highway department. The original of these forms is submitted by project personnel to the central office of the West Virginia Department of Highways. The data on the forms are evaluated for completeness and correctness by the computer. If errors or missing data are found, they are identified and printed out. After corrections have been made, the data are permanently stored on magnetic tape. Various subroutines are used to evaluate the data. Two of the most significant ones are (a) a statistical analysis of the percentage of density for the project on a timed sequence and on the completed project, which includes an evaluation of the uniformity of the embankment and subgrade density, and (b) an analysis of moisture control on a timed sequence and on the final project.

Organic Test

Organic material contained in the material used to form the embankment and subgrade is limited to 7.5 percent by weight. At this limit, the possibility exists that the organic material could occupy as much as 15 percent of the volume of the material being placed. Should the percentage exceed that specified, it could result in excess consolidation or an adverse effect on the strength of the material or both. Test method MP716.04.20—Determination of the Organic Content of Soils by the Dry Combustion Method—determines the organic content at a controlled temperature of 440°C (824°F) for 5 h (4).

Lift Thickness

Lift thickness must be measured three times per lift and documented by the contractor.

Quality Control

MP717.04.21—Guide for Quality Control and Acceptance Plan for Embankment and Subgrade—is specified in the contract documents and is intended to be used by the contractor for designing his or her quality control system. It requires that the contractor's plan be submitted at the preconstruction conference, and it defines the acceptable test procedures. A direct-transmission type

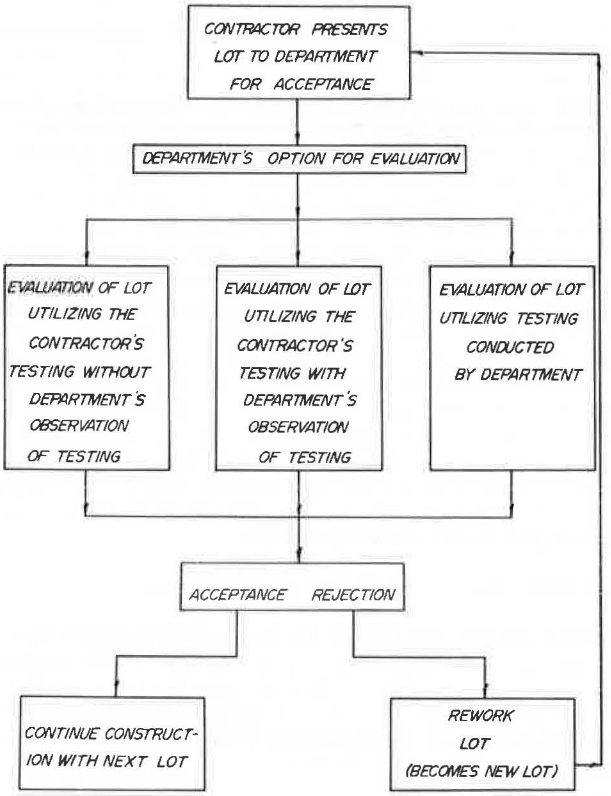


Figure 2. Procedure for acceptance of embankment and subgrade.

of nuclear gauge is required for density testing. The minimum number of tests, reports, and measurements per lot is indicated for the several types of gradation in the material placed. The reports for proof rolling are to include the make, size, and compactive force of the roller and the number of rolls performed on each lift. The plan is also to include the time schedule and distribution of data.

The document is to include the names of the contractor's personnel who are responsible for quality control and liaison and the personnel who are conducting the tests and measurements. It is recommended that personnel who conduct the density tests be certified compaction technicians. The West Virginia Department of Highways has been conducting a certification program for departmental personnel for 9 years. This program, which includes a written and practical examination, has been extended to industry personnel in conjunction with the Contractors' Association of West Virginia. The department also conducts a training program that has been extended to industry personnel. The training program includes programmed instruction, lectures, and practical exercises. Audiovisual tape instructions are also used where "hands-on" training is not practical.

Lots Offered for Acceptance

Acceptance of a Lot

The highway department has the option of acceptance of the contractor's lots according to the methods shown in Figure 2. Say the percentage of a lot within a tolerance of 80 percent has been retained. An analysis of the data finds that the department has approximately a 6 percent probability of accepting substandard material that is evaluated by five density tests. Although the contractor's actual risk cannot be determined before he or she performs the work because the risk is dependent on control by the contractor, an average value can be estimated. Therefore, based on historical data from the research project that were used to determine an average quality of density, a contractor with adequate control could expect to have approximately a 3 percent probability of rejection on acceptably densified material. It should be noted that a very important feature of the acceptance plan used is that, if the contractor's quality control of density is poor, his or her risk is greatly increased.

A recent evaluation of the demonstration project that was constructed by using these controls shows that the project has performed satisfactorily for 5 years with negligible settlement or pavement failure. The evaluation of the percentage within tolerance indicated that, had a value greater than 80 percent been used, it would have been necessary for the contractor to have a much smaller range in dry density per lot or a higher average density or both; otherwise, as indicated by the performance of the project, many more lots would have been unnecessarily rejected.

Rejection of a Lot

When a lot fails to meet the specifications, reworking is required before another lot can be placed on it (Figure 2). Testing of the reworked lot for acceptance is done at the expense of the contractor if the highway department conducts the testing. The unit cost for testing of a reworked lot when tests are conducted by the department is published in MP109.00.20—Basis of Charge for Additional Testing. The amounts are updated to reflect current testing costs. The cost is for five tests since that is the minimum acceptable for evaluation. Since reworking a lot in effect produces a new lot, the reworked lot is evaluated only by the five tests conducted after reworking.

SUMMARY AND CONCLUSIONS

Current quality assurance specifications in West Virginia have been reviewed by industry personnel, and informative seminars have been given for industry management. The specifications have been received quite favorably to date. During the first 6 months of the certification program for industry personnel, 68 people have entered the program and 24 have been certified.

The cost of this type of specification for embankment and subgrade can only be evaluated after several years of use. The cost would normally be reflected in the unit price bid for the unclassified excavation. That cost was \$1.54/m^3 (\$1.18/yd^3) for the research project. The average cost for all types of roadways and construction for unclassified excavation in 1970, the year the project was bid, was \$1.67/m^3 (\$1.28/yd^3). It was anticipated that the bid might be high because of uncertainty on the part of the contractor about this type of specification and because it was the first time the highway department had required this type of quality control on earthwork. It would appear, however, that for the research project the required quality control did not materially affect the contractor's bid.

The current specifications require that the contractor be responsible for quality control of the embankment and the subgrade. This is quite appropriate since the contractor has the fundamental control of the work process. The current specifications for embankment and subgrade are not true end-result specifications because of the nature of the material placement.

As determined by the research demonstration project, the quality assurance specifications discussed here do offer a level of quality control and acceptance that interferes as little as possible with the contractor's management of his or her processes. Further, the research demonstration project and the current specifications accept the premise that there will be a certain percentage of material that will fall below a given standard. The method of acceptance makes reasonable estimates of substandard material. These estimates are used to keep nonspecification material to a minimum. Because the method of acceptance requires control of variance in the quality control of density, it encourages a more uniform density in the final product.

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