gree 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.

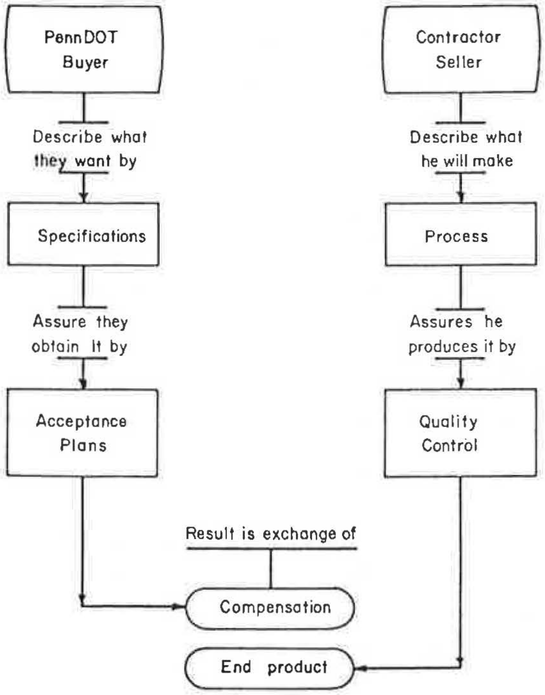
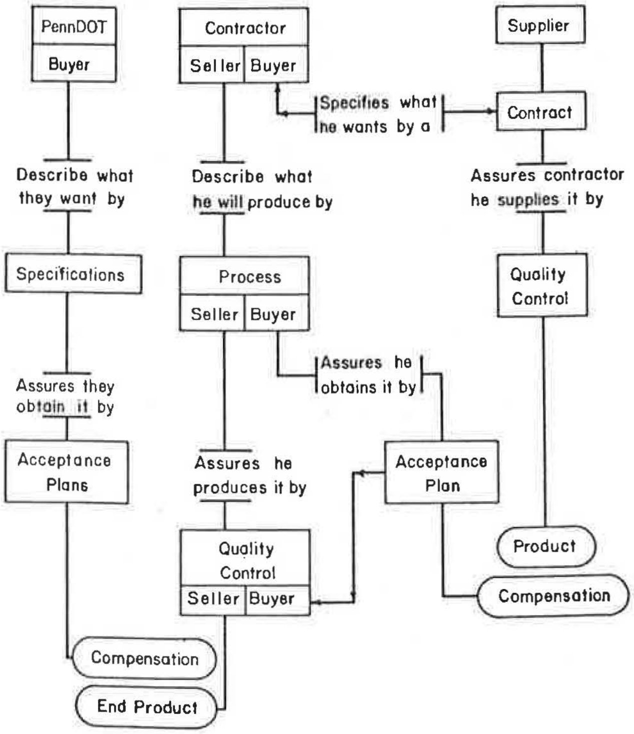


Figure 2. Three-party relation of quality control and acceptance plans.



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 main-line 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

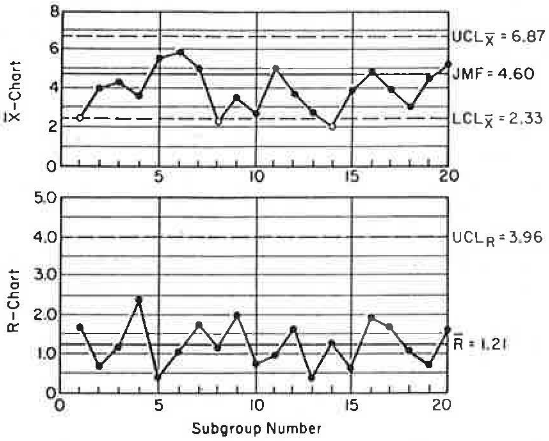
Dilemma of Contractor and Material Supplier

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. $\overline{X}$ 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 $\overline{X}$ 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 $\overline{X}$ 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 $\overline{X}$ 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 $\overline{X}'$ 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 ($\bar{X}$ 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 $\bar{X}'$ and standard deviation σ' are needed. There are two ways in which these parameters may be obtained: (a) $\bar{X}'$ and σ' are known (for a well-defined process), and (b) $\bar{X}'$ 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 $\bar{X}'$ 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 $\overline{X}$ 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.

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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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