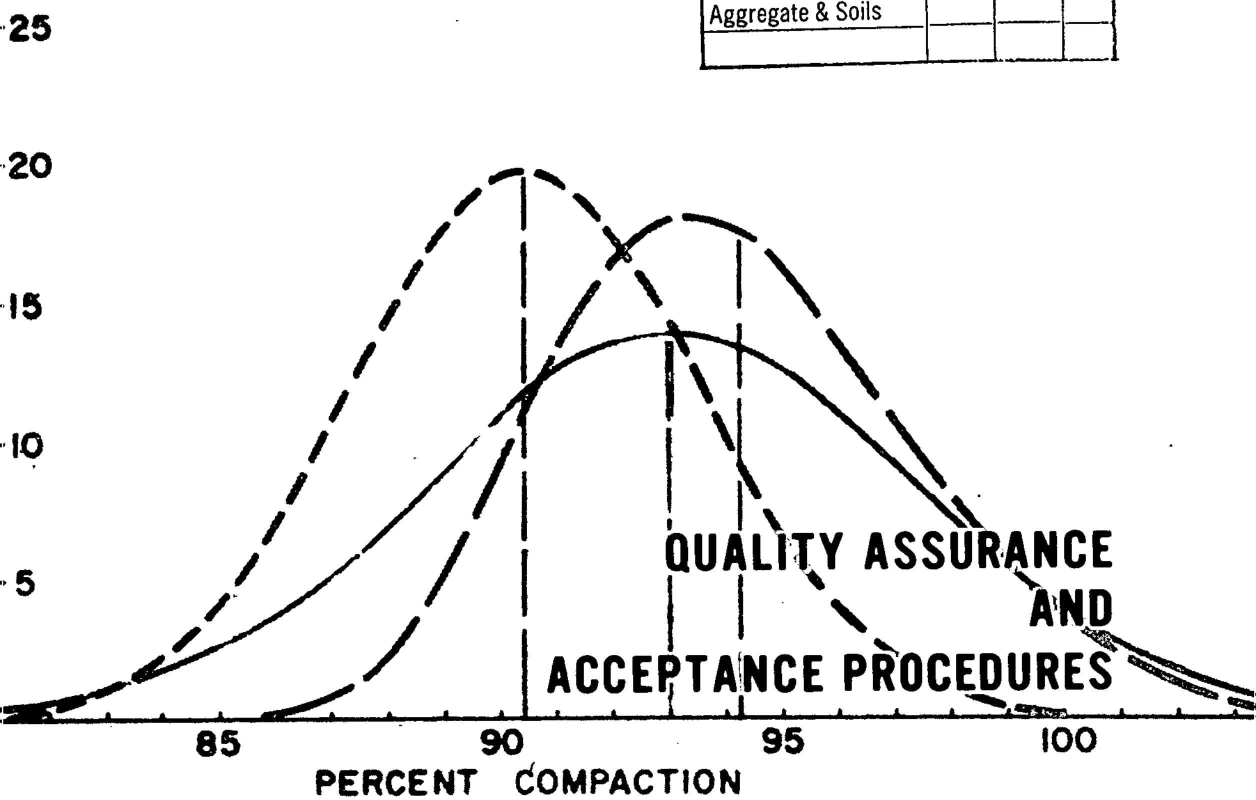


# QUALITY ASSURANCE AND ACCEPTANCE PROCEDURES

HRB Special Report 118

HIGHWAY RESEARCH BOARD

National Research Council
National Academy of Sciences
National Academy of Engineering

# QUALITY ASSURANCE AND ACCEPTANCE PROCEDURES

Subject Area
33 Construction

Special Report 118

HIGHWAY RESEARCH BOARD
Division of Engineering
National Resaerch Council
National Academy of Sciences
National Academy of Engineering
WASHINGTON, D.C., 1971

ISBN 0-309-01848-X

Price: $1.60

Available from

Highway Research Board
National Academy of Sciences
2101 Constitution Avenue
Washington, D.C. 20418

# Foreword

This Special Report was prepared to summarize the state of the art and highway department needs in the area of quality assurance and acceptance procedures.

When the HRB Committee on Quality Assurance and Acceptance Procedures studied the problem of writing a state-of-the-art report on quality assurance, it decided that a new approach was needed. Members of the committee had participated in writing other state-of-the-art reports that required 3 or 4 years to complete. Recognizing the rapid changes in the field that would make a report 3 or 4 years old practically useless, the committee thought that it was imperative that the period between starting a state-of-the-art report and finishing it be reduced as much as possible. To shorten this period, the total area of the state-of-the-art report was divided up and assigned to members of a task force. Each member was responsible for writing a brief evaluation of his topic. This evaluation would be his personally and not that of the committee or the task force but would have the overall committee review and approval. The committee thought that such a report written by one thoroughly familiar with the state of the art in a given area could be very helpful to those not directly involved with quality assurance. These reports constitute Part 1, State of the Art. For those people who want more detailed information, there are other services, such as the Highway Research Information Service.

Part 2, Highway Department Needs, summarizes the committee's thoughts on the future quality assurance and acceptance procedures needs in specifications, laboratory standardization, and information-handling systems.

The HRB Committee on Quality Assurance and Acceptance Procedures wishes to thank the Task Force on State of the Art, R. L. Davis, Chairman, and the authors of the papers in Part 1; and the Task Force on Highway Department Needs, Garland W. Steele, Chairman, F. E. Legg, John L. Beaton, and George W. McAlpin for their work.

—Leo D. Sandvig

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# PART 1:
# State of the Art

# Aggregates

D. L. Bloem*, National Ready Mixed Concrete Association

Statistical procedures to monitor and regulate the quality of aggregates for highway work have been slow in gaining application. There are several reasons: (a) with the exception of grading, the properties of aggregates significant to their performance are not quantitatively determinable by existing test methods; (b) the required level of a significant characteristic (such as hardness, strength, soundness, or freedom from contaminants) depends on application and exposure in ways that are not at present quantitatively measurable; and (c) a clear-cut delegation of responsibility for aggregate performance among the producer, contractor, and highway department has not been defined.

Ironically, the lack of significant test methods for quality has not completely forestalled the use of statistical bases for acceptance. Studies have been and are being made (1) to establish realistic statistical parameters for the conventional aggregate tests such as absorption, specific gravity, abrasion resistance, and soundness. Eventually these should provide the basis for a more realistic enforcement of the disparate specification limits imposed by individual highway departments even though better statistics will not improve the significance of the tests themselves. In other words, by using realistic sampling plans and allowing properly for sampling and testing variations, as well as actual normal variability of the aggregate in responding to a particular test, it will be possible to arrive at enforceable acceptance criteria for control purposes. Ability to discriminate between good and bad sources will not be improved until tests become available that correlate quantitatively with a significant aspect of performance. On the other hand, statistical monitoring of a particular source may lead to improved uniformity by encouraging the use of mining and processing methods that will minimize test variability and the frequency of failure.

It is in the surveillance of gradation for both control and acceptance purposes that statistical concepts are showing greatest promise. As implied earlier, grading is the only significant aggregate property that can routinely be measured with accuracy. Even so, the reliability of sieve analyses is often in question because of sampling errors, aggravated by segregation that occurs during handling and storage.

Recent researches have shown the way to sampling plans and techniques that, coupled with sound statistical methods of interpretation, provide realistic criteria for enforcement of grading limits (2, 3, 4, 5). It has been shown that variance in sieve analyses can be divided into a batch-to-batch component, which relates significantly to performance of the aggregate, and a within-batch component, which reflects combined errors of sampling, testing, and the inherent variability of particle size distributions within a granular material. A proper specification must stipulate a sampling plan that will measure average grading of each lot of aggregate and also indicate the frequency with which batch-size quantities can be expected to lie outside acceptable limits. With a sound sampling plan and the use of proper sampling and testing techniques, the results provide a basis for decisions on acceptance or assessment of penalties. Details are given in other reports (2, 3, 4), and additional explanation and examples are also given in an earlier report (6).

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*Deceased, January 12, 1971.

The statistical acceptance criteria are aimed primarily at assuring satisfactory performance of aggregates in their end use—concrete, bituminous mixtures, base courses, etc. Acceptability at the point of use depends not only on the gradation and uniformity of the aggregate as produced, but also on the amount and methods of handling and storage between the plant and production site. These latter operations are often handled by persons other than the producer, and he has no control over them. For this reason, many aggregate producers are undertaking statistical quality control monitoring at their plants to ensure that the aggregate as furnished to each customer meets his grading requirement. Depending on circumstances, control measures may range from simple attention to handling and storage to involved systems of size separation and reblending to permit "tailoring" gradings to the needs of individual customers.

In summary, sound statistically based methods are available for use in controlling and evaluating the acceptability of aggregate gradation. Statistical data on aggregate tests other than sieve analysis are being accumulated that should eventually permit establishing acceptance criteria on a sound statistical basis (1). Their application should reduce controversies between producers and purchasers and may lead to improved uniformity within sources. No statistical approach can overcome the inability of existing test methods to measure quantitatively the significant performance characteristics of aggregate.

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## Bituminous Construction

C. S. Hughes, Virignia Highway Research Council

At present it is obvious that most state highway departments, as well as the Federal Highway Administration, are aware that statistically derived tolerances need be obtained. This awareness was revealed in a number of recent meetings (such as annual meetings of the Highway Research Board and the Association of Asphalt Paving Technologists, and the National Conference on Statistical Quality Control Methodology in Highway and Airfield Construction held at the University of Virginia) that included presentations on materials variability and statistically oriented specifications. It is not so evident that the highway departments are ready to use the statistically derived tolerances with end result specifications and to effect a total sampling plan, nor is it evident that contractors see the immediate need for introducing quality control procedures into their processes, mainly because the necessary incentive has not been provided.

The change to statistically oriented specifications has been and will be slow, primarily because the highway industry is reluctant to abandon the traditional methods and specifications that have been used for many years and go to new, unfamiliar techniques that are providing tolerances much larger than intuition has told us are necessary, even though the larger tolerances are demonstrably sound.

There are generally 4 steps involved in reaching a fully implemented statistical specification. The states furthest along in this program have reached the fourth step, but the majority of states have not yet begun step 1 or even made assumptions on step 1 and jumped to step 2.

The first step is the establishment of a realistic variability by either making statistical analyses of historical data or installing a separate sampling system to obtain data under a controlled procedure. The obvious advantage of the former is the saving of time, whereas the advantage of the latter is the assurance of more reliable data through the elimination of sample bias, including the discarding of some test results. Also, very few historical data have been collected by random sampling.

The variabilities have quite often been separated into testing variability, sampling variability, and materials variability. Although this separation is quite informative, particularly from a research viewpoint, it is not necessary to the establishment of realistic tolerances—as long as the same testing and sampling procedures are used in enforcing the specification as were used in collecting the data on which it was established. For instance, if tolerances are based on asphalt content data obtained from extractions by Rotorex, the same tolerances would probably not be realistic for extraction by Reflux.

There are probably about 25 highway-oriented agencies that either are still working on step 1 or have proceeded further.

The second step is the use of variability to establish realistic tolerances. Two broad options are available: either (a) merely insert the new tolerances into the conventional specifications, or (b) change the specifications entirely by adopting complete acceptance plans. For those taking the first option, this ends the immediate statistical program; but as shown later there are many other items, in addition to tolerances, that should be considered from a statistical standpoint.

The most popular currently used or proposed tolerances for bituminous concrete gradation and asphalt content may be of some interest. The tolerances, given in Table 1, are the amount the average of 5 samples may vary from the chosen job mix. Most agencies have chosen 5 as the number of samples for averaging to determine the acceptability of each lot; however, many use the average of 4, and at least one uses the average of 2 samples.

TABLE 1

TOLERANCES OF $\bar{X}_5$ FROM JOB MIX

| Sieve Size | Percent Passing ±Tolerance[a] | Sieve Size | Percent Passing ± Tolerance[a] |
|---|---|---|---|
| + 1 in. | 4.5 | No. 8 | 4.0 |
| ¾ in. | 4.5 | No. 30 | 3.5 |
| ½ in. | 4.5 | No. 50 | 2.5 |
| ⅜ in. | 4.5 | No. 100 | 1.5 |
| No. 4 | 4.0 | No. 200 | 1.0 |

[a]Tolerance on percent asphalt = 0.4.

There are some indications that the tolerances should be more dependent on the amount of material retained on a particular sieve rather than on the size of sieve. This would mean that 1-, ¾-, and ½-in. sieves may not need as large tolerances as they now have; however, at present the consensus is as given in Table 1. There are about a dozen agencies that have established tolerances based on either their own data or those of other agencies.

The third step is the use of the new specification in a simulation. So as not to proceed precipitously into a new and untried specification, most agencies first use a simulation process. This may be done in at least 2 ways. Most agencies first use the specification in a research-oriented project on which the contract is actually governed by the conventional specification. New York State has a different approach in that a computer is used to produce mix data that can then be tested statistically and compared to model specifications. This approach allows a great deal of flexibility and also saves much time.

The simulation affords an agency the opportunity to test the specification, particularly the number of samples and sampling procedure, under realistic conditions and to modify it if necessary. This stage generally reveals not only differences in test results, but also the need for basic philosophical decisions concerning such items as retesting and referee procedures. There are about 10 agencies that are using or have used the simulation procedure.

The fourth step is the use of the statistically oriented specification as the basis of acceptance in a contract. There are several states (Louisiana, California, Illinois, and West Virginia) that are just completing a version of a statistically defensible specification and that should soon start letting contracts under it. States that are somewhat further along in the program and are actually accepting materials under statistical specifications are South Carolina, Virginia, New Jersey, and Mississippi. In Mississippi the specification is limited to a density requirement, but the other states are concerned with asphaltic concrete production. Virginia has had a specification based on statistically derived limits for acceptance of asphaltic concrete compaction for more than 4 years, but only in the past year and a half has it accepted asphaltic concrete production based on statistical limits. South Carolina has accepted asphaltic concrete on 6 contracts and has let 12 additional contracts. Virginia has completed 5 state-financed contracts, has several more in process, and has recently received approval of the Federal Highway Administration to use its statistically based specification on federally financed projects.

## TYPICAL COMPONENTS OF STATISTICAL SPECIFICATIONS

There are several components more or less inherent in all of the statistical specifications, whether they are in the simulation stage or actually in use. Some specifications include all of these items; others do not.

1. Lot Size—This is the amount of material that is to be judged acceptable or unacceptable. It is somewhat arbitrary but is generally considered to be a function of time (a day's production) or a function of production (for example, 2,000 tons). There are several considerations that must be recognized in establishing the lot size; for in-

stance, one must consider the consequences of having to reject or adjust payment, and the number of tests must be realistically compatible with the lot size.

2. Number of Samples—The number of samples that will be taken from each lot in judging acceptability must be specified. Currently, as mentioned previously, this number ranges from 2 to 5, with most states using 4 or 5.

3. Acceptance of Central Tendency—To determine the location of the mean or central tendency of the lot, the sample average is used. The average is then compared to the process tolerance around the job mix to determine acceptability. Some states, such as California, use a moving average with compatible limits to determine acceptance of this production characteristic. This measure has an integrating or smoothing effect on the test results and minimizes individual fluctuations; it is also a more continuous function than simple averages.

4. Acceptance of Variability—At present, there are at least 3 methods of limiting variability. The first method uses a limit on the amount any individual sample may vary from the central tendency. The advantage of this method is that it can be determined immediately whether or not the lot is acceptable. The disadvantage is that it is not a strong statistical technique for determining material that is actually out of specification. The second method limits the size of the standard deviation for, generally, a large amount of production. The advantage of this method is that it is more fundamental from a statistical standpoint and requires the recognition of variability. Calculation of standard deviation is a very strong incentive to improve the educational attitude of the statistically uninitiated. The third method, the use of the range to estimate variability, uses some of the advantages of both of the others and may eventually be used more widely than either of them. Typical limits used with the first two methods are given in Table 2. It should be noted that these limits are not compatible between methods. This lack of compatibility reflects the different thinking and test results that exist between agencies.

5. Other Acceptance Criteria—Some agencies have chosen to use acceptance criteria other than the ones previously mentioned. There are numerous other criteria; some being strongly considered include percent defective product, quality index (which combines acceptance of central tendency and variability into one factor), and limits based on sequential analysis.

6. Adjustment of Bid Price—Because this new form of specification is based on acceptance and leaves product control up to the contractor or producer, there is a necessity to provide for action when the product does not meet the acceptance criteria. Since for most highway products removal is impractical because of cost and difficulty, the product is used with a reduction in the bid price. If an adjustment is required, it may vary from as little as 1 percent to as great as 30 percent of the bid price. There is also some sentiment toward a positive adjustment or increase in bid price if the product is unusually uniform and close to the job mix formula. Highway administrators in several states are looking carefully at this concept.

TABLE 2

TYPICAL LIMITS USED FOR STANDARD DEVIATIONS AND INDIVIDUAL TEST RESULTS

| Sieve Size | Percent Passing | |
|---|---|---|
| | ± Individual[a] | Std. Dev.[b] |
| 1 in. | 9 | 4.5 |
| ¾ in. | 9 | 4.5 |
| ½ in. | 9 | 4.5 |
| ⅜ in. | 9 | 4.5 |
| No. 4 | 9 | 4.5 |
| No. 8 | 8 | 4.0 |
| No. 30 | 6 | 4.0 |
| No. 50 | 4 | 3.0 |
| No. 100 | 3 | 2.5 |
| No. 200 | 2 | 1.5 |

[a]Individual limits on percent asphalt = 0.6.
[b]Standard deviation on percent asphalt = 0.3.

7. Control Charts—In an attempt to point out possible control procedures the contractor may use to control his process, control charts are being used widely. Often the data plotted on these charts are actually acceptance data, but encouragement for the contractor to make his own tests is very strong. In some cases the control charts are used to require the contractor to change his material or to shut down if the product gets out of control; but in most instances the results are merely posted so that the contractor can use them as he sees fit.

8. Retesting and Referee Procedures—As mentioned previously, the limits estab-

lished are completely dependent on the number of samples used for acceptance. This means that if a retest is necessary because the results are questionable and additional samples are necessary for clarification, the tolerances must be adjusted to agree with the sample number; and as the sample number increases, the tolerance to which the average is compared must be decreased.

## SUMMARY

The use of statistically oriented end result specifications has caused some problems, and certainly they do not solve all of the engineering or materials problems, but they can solve many of the problems that indefinite and arbitrary specifications have caused in the past. The most serious problem is the lack of statistical training. The training and manpower problems that face the contractor as he assumes more control of his process cannot be dismissed easily nor can they be ignored forever. Statistical specifications are being and will continue to be increasingly used because of their clarity and defensibility. The highway industry will improve its operation if it recognizes the benefits they can provide and acts to implement the necessary procedure as quickly as possible.

# Concrete Construction

Peter Smith, Ontario Department of Highways

Experience shows that concrete meeting the quality requirements of most current specifications for highway pavements and other structures can provide satisfactory service. The objective of quality assurance in its broad sense is to make certain that this will happen by design rather than chance, and at minimum cost. The term quality control has become widely used to describe the process by which this is achieved through the testing and inspection of the constituent materials and of the concrete as it is produced and when incorporated in the work. In fact, although in present practice they are often combined, there are two distinct elements to this process. The first is product control by the contractor to ensure that the concrete as produced and used meets the specification, and the second is the acceptance of the product by the owner as part of the completed work.

Product control is needed because each of the materials incorporated in the concrete and each process used contributes variations of their own to the end product. These variations occur both within a batch and from one batch to the next. Some are naturally occurring random variations that cannot be controlled. Others, and these are usually much larger, are the direct result of malfunctioning processes or human action, and these can be detected and changed. The effects of variations are often interdependent and cumulative. For example, if control is by slump and the sand content changes, this alters the water requirement, air content, etc. Furthermore, it should be borne in mind that accumulation of variance, including errors that arise from sampling and testing used to detect variance, is not arithmetic. For this reason, and because of the heterogeneous nature of concrete, the effect of variations in component materials and processes can have far-reaching and probably detrimental effects if left unchecked.

Acceptance of the product requires confirming that it complies with the specification. Ideally this should be done by examination and testing, as needed, of the concrete after all operations concerned with its manufacture have been completed and it is in place in its final form in the work. In practice, however, acceptance at an earlier time may be advantageous to both the contractor and the owner because it is difficult and costly to remove and replace defective concrete work. For this reason, acceptance inspection and testing of the component materials and of the concrete as it goes into the forms have been standard practice although owners have endeavored to retain a contractual right of later rejection. To avoid apparent duplication in inspection and testing, this naturally led to product control and acceptance judgment becoming combined for many years on most jobs in one and the same operation. The results of this and anticipated changes are discussed later.

The properties of concrete required by the specification, both when plastic and after hardening, and of the constituent materials—cement, coarse and fine aggregate, water, and any chemical additives or admixtures—are based on methods of test and limits prescribed by AASHO (18), ASTM (17), CSA (11), or other recognized standards. Quality assurance requires that the constituent materials be inspected and tested before use and that, taking into account the necessary features of the particular materials to be used, they be handled, proportioned, and mixed to produce concrete that in the plastic state will remain workable and uniform during transportation and placing, and will, after consolidation, finishing, and curing, display the required properties of strength, durability, impermeability, appearance, etc., in the completed work.

There are still serious gaps in our knowledge as to what variations in concrete and concrete materials can be tolerated before adverse effects show up. Often there is no abrupt change for the worse, and this makes the setting of limits (and rationally their enforcement) often a matter of judgment based on experience rather than fact. The significance of the available methods of test has been reported (3), and it should be kept in mind that uncertainty also exists that it is always a relevant property that is specified and, hence, controlled. Often properties are specified simply because a convenient or conventional method of measuring them exists. Much effort may then be put into their control on the job. This is often beneficial; e.g., low slump probabilities imply a low water-cement ratio. However, it is likely that injudicious control may, at the same time, be adversely affecting some desirable property. For these and other reasons, the perfect concrete specification in respect to quality has not yet been written. In spite of this, experience over many years has indicated that field control of (a) strength (as determined by cylinders or cores broken in compression or beams broken in compression or beams broken in flexure), (b) workability and indirectly water content (as determined by the slump, Kelly ball, or other test), (c) air content (as determined by the pressure or a volumetric method), (d) gradation and cleanliness of the aggregates and adjustment of the mix proportions to compensate for moisture in the aggregate, (e) batch weights for compliancy with design mix proportions (by visual inspection or printout), and (f) quality of constituent materials (by both sampling before and during use for laboratory testing), together with inspection of the production, use, consolidation, finishing, and curing processes can provide satisfactory quality assurance on most jobs.

With the exception of the air test and refinements such as automatic plants with control of slump, moisture content, and printout of batch weights, all the other control elements listed have existed essentially in their present form for 50 years. The main change has been in the manner in which they are used and the interpretation and application of the results.

The "conventional" approach taken for many years to assure quality in concrete used in highway work is typified by that reported in Illinois (20). Using their own well-trained staff, the Illinois State Highway Department undertook the complete inspection and testing of the materials and the concrete. The contractor was considered to have done his job correctly if he drew his aggregate from approved stockpiles produced under state inspection and his cement from state-tested and sealed silos, and complied in every respect with the direct instructions given as the concrete was produced and used to reject out-of-specification concrete or make corrections to the next batch. For this purpose, frequent "representative samples" were usually taken at fixed intervals and tested for compliance with exact specified limits, and simple control charts—such as bar graphs for strength, aggregate grading curves, and slump ranges—were used as decoration on field office walls.

This system worked well in generally improving quality where previously it had been poor, probably because at least tests were made and persons knowledgeable in making good concrete were there to see that things were done right. However, many people (14) recognized that this approach had limitations that, by not properly taking into account such inherent variations in concrete as, for example, its strength, made the specification of absolute limits unrealistic and often costly. A major advance was made by introducing a statistical basis for the analysis, evaluation, and specification of concrete strength as the overall criteria for concrete acceptability. This permitted the proportioning of concrete to meet the specified requirements without reference to such safeguards as a fixed cement factor, with consequent savings in cost. Following its success on the construction of the Illinois Toll Road and its standardization by ACI Committee 214 (7), this "How Good Is Good Enough?" approach (5) gained a wide following. Most highway authorities, however, continued to undertake the whole of the inspection and testing operation and to manually prepare the necessary statistical analysis and attendant control charts showing moving averages, required averages, coefficients of variation, etc.

The increased pace of construction, the delays involved in decision-making while awaiting evaluated test results, and often the sheer impossibility of sampling, inspecting, or influencing the increasingly sophisticated and automated plants coming into use caused frustrations that have led to the questioning of both the "conventional" and "how good is good enough" approaches for the control of concrete quality on logical, economic, and legal grounds. Some of the points raised have been as follows:

1. Sampling plans are required because there can be no such thing as a single representative sample (1, 2, 3).
2. Errors due to sampling and testing and effects of the naturally occurring variations in materials were not properly recognized. Tolerances were required on most specification limits (1, 2, 3).
3. Assumption of dual responsibility by the owner for both product control and for acceptance was not justified, and that control of concrete quality during production and use must rest with the contractor (4, 9).
4. Under current specifications, the risks to the producer of having good material rejected and to the owner of accepting poor material were not soundly or equitably based (2, 13, 15, 16).
5. The impact of the automation of batching and mixing plants or other processes was not taken into account (10).
6. The rapid pace of concrete production and use outstripped the currently available methods of testing, inspecting, and evaluating the results (8, 10).
7. Fact rather than opinion should govern acceptability and provide justification to the auditors for payment for the work (2, 3, 15).
8. Possibilities of financial bonus or penalty payments for quality that exceeds or falls short of the specified standard should be considered (13).
9. In many other industries, process control and product acceptance were on a different and apparently more satisfactory basis. Their experience and methods should be equally applicable to concrete (4, 9).

Possible solutions to these questions are currently the source of much research, debate, and anguish. Idealized specifications employing the principle of substantial statistical compliance have been developed (3), although their full acceptance has not yet proved desirable or feasible on the basis of results to date. Investigations have been undertaken to examine the validity of sampling and testing based on random statistical concepts within overall quality assurance plans (13, 19, 21). The risks inherent in concrete production in relation to current specifications, and suggestions for more realistic ones have been examined (13, 16). Precision statements are being introduced into most test methods (1, 17). Dissatisfaction with the adequacy of conventional methods of inspection and testing has been documented, together with areas in which either improvements or new methods are required (8). Faster methods of testing [for example, accelerated strength tests (6) or determination of cement and water content (12)] are being developed into practical use. Systems approaches are being introduced (10) in which the data obtained during quality control at the time of construction are being evaluated by computer processing and also stored for subsequent retrieval for use in subsequent performance studies or for material selection and the drafting of specifications for future work.

There is every promise that these and other developments will lead eventually to better procedures for quality assurance in concrete than are currently available. However, it must be recognized that any job will benefit immeasurably from the application of control measures currently available. This must, however, be meaningful and realistic control planned on a routine basis and relentlessly carried out by trained personnel using properly conducted tests on which to base decisions as to changes needed in the various materials or processes in use or on which to judge acceptance.

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## Construction Practices

Clarence E. DeYoung, Iowa State Highway Commission

The first application of statistical quality control in American industry was made by Dr. Walter Shewhart of the Bell Telephone Laboratories during the 1920's. The development of this new methodology and its acceptance by other industries in the United States was very slow until the event of World War II.

About this time a new concept, statistical decision, was introduced. The Department of Defense, which was faced with a massive procurement program, recognized the utility of this technology and pioneered the general development and application of statistical-based process control and acceptance concepts to industrial products. This effort stimulated its application to a great variety of industrial products.

The rather startling experiences with construction control at the AASHO Road Test and the institution by the Bureau of Public Roads and state highway departments of a "record sampling program" are considered to have generated the first real active effort by highway engineers to explore the use of statistical concepts as a tool for the solutions of many quality assurance problems. Dr. Robert F. Baker, former Director of the Office of Research and Development of the Bureau of Public Roads, is cited as one of those who recognized its power and aggressively promoted its use. He believed this development should contribute as much to our ability as engineers as did the advancement of the elastic theory in the 19th century and the use of computers and new construction equipment of the 20th century.

The creeping pace for adoption of statistical concepts in the control and acceptance of highway construction can be compared to the evolution of the computer. During the past 6 years engineers have become knowledgeable on the subject and, with this, resistance on the grounds of practicality is diminishing and realistic progress has started.

Some of the first applications of these concepts were made on the Garden State Parkway in New Jersey and on the Illinois Toll Road. The first state to start using probabilities in the acceptance of construction was Mississippi, where a combination control chart-acceptance plan with variable sample size was developed and included in the 1967 Standard Specifications for the acceptance of soil-cement base and bituminous hot-mix construction. Now at least 10 other states and the Bureau of Public Roads, in their direct construction operations in Regions 8 and 9, are accepting construction or portions of the construction process with specifications based on statistical concepts. States included are California, Louisiana, West Virginia, North Dakota, South Carolina, Virginia, Illinois, New Jersey, Utah, and New York. Of this group, New York and California are accepting the process, while the remainder are accepting on a lot-to-lot basis.

Four states and the Bureau of Public Roads Region 15 have conducted recent simulation studies. In these cases, construction was accepted by the usual methods, and separate crews performed parallel sampling and testing to test the criteria for and requirements of various statistical plans. Those involved in this category include Ohio, Nebraska, Michigan, Indiana, and the Bureau of Public Roads. In addition, New York has completed a prototype model for computer simulation on an asphalt plant's production. New York's approach allows a wide latitude for experimenting with various control and acceptance schemes with minimum sampling.

Many states either in cooperation with the Bureau of Public Roads or by themselves have measured the variability of many facets of construction and are continuing to do so. Active studies using HPR cooperative funds are under way in Minnesota, Georgia, Connecticut, Pennsylvania, and Maine. Of course, many other states are exploring various concepts in the informal way. Iowa has used a variables plan based on unknown standard deviations and averages to determine what variations should be considered normal for present acceptable construction and to provide for automatic identification of construction where establishment of reasonable compliance with the specification may require some administrative action (1).

In summary, a total of 36 states have actively been engaged in some form of study or application of statistically oriented specifications for a control and acceptance of construction. More than one-third of these states now are using a statistically designed specification as a standard specification or as a special provision. Application of these concepts is developing at about the same rate in the United Kingdom and the Canadian Provinces.

This is a significant accomplishment considering that the words standard deviation and mean were words foreign to almost all of us just a few years ago.

The general consensus seems to be that more inventiveness is needed in applying statistical concepts to highway quality assurance and acceptance procedures and that adoption of a "standard" plan or plans is not feasible at this time. However, a number of acceptance applications have proved to be sound and are in general use at this time. Many of them are based on the work of G. J. Lieberman and G. J. Resnikoff performed under the sponsorship of the Office of Naval Research (2, 3). "Sampling Plans for Inspection by Variables" by Lieberman and Resnikoff are suitable for highway applications and were used on the AASHO Road Test (4, 5). The statistical applications embodied in the futurized version of federal project specification, FP-61 (6) are the basis of many specifications being written.

The pamphlet on "Quality Assurance Through Process Control and Acceptance Sampling" issued by the Bureau of Public Roads (7) and NCHRP Report 17 (8) are useful references on the principles of statistical quality assurance and acceptance in highway construction for those who are not versed in mathematical statistics.

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## General Materials

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The past few years' literature survey would indicate that very little has been said or done about quality assurance and acceptance plans for general materials in highway construction. These general materials cover a wide range of manufactured products including: bituminous materials, hydraulic cements, structural steel, paints, pipes, posts, guardrails, and similar other items.

These items are, for the most part, manufactured under the control of the producer with the state performing acceptance sampling only. In fact, this seems to be the prime reason for the states to steer away from this aspect of quality assurance research. On the other hand, no other highway material category would better fit the total quality assurance program than the general materials.

There is a definite need for development of acceptance sampling plans for material such as asphalt cements or liquid asphalts. The manufacturers of this extensively used material do not have as stringent a quality control set up as some of the other manufactured items. California (1), as a result of a detailed investigation, has set up a tentative method for determining compliance with penetration test requirements for paving grade asphalt. Various factors affect or influence the development of penetration and liquid asphalt specifications. The crude source, method of refining, and performance of asphalt in pavements are some of the major factors that need consideration. Winnitoy (2) has discussed some of the more common tests with respect to the variability and desirable limits.

However, hydraulic cements are purchased under standard specifications, and rarely does a shipment fail to meet the requirements. The reason is that the specifications are too broad. Furthermore, most test results quoted are on composite samples that easily hide the variations. In view of this, a systematic acceptance plan, which would reduce the testing time (and consequently, savings in dollars), would seem justified at the present time (3).

In the manufacture of steel, rigid inspection and control procedures are exercised by the various steel mills. Qualified national organizations such as ASTM, AASHO, AWS, and AISC, representing producers and consumers, have thoroughly prepared specifications for practically all phases of construction. As a result of their efforts, duplication by state agencies would result in increased cost due to testing and inspection. Brumer and Stahl (4) discuss some of the problems involved in quality control of structural steel.

All in all, it can be said that (a) a need exists for development of suitable acceptance plans for some of the manufactured products, (b) the reduced sampling plan of ASTM and AASHO for some of the manufactured products should be utilized by the states until such time as additional research would dictate otherwise, (c) information on the performance of tests on traffic paints should be made available for adequate development of acceptance specifications, and (d) national organizations such as ASTM and AASHO should be made cognizant of the problems of acceptance of manufactured products and should be asked to help in the solution.

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# PART 2:

# Highway Department Needs

## Highway Department Needs

In a discussion of obtaining the level of quality of highway construction necessary to perform its intended functions, quality assurance in its simplest terms is defined (1) as a 3-step process:

1. What do we want?
2. How do we order it?
3. How do we determine that we got what we want?

Most quality assurance programs have stressed answering question number 3.

These three questions are interrelated. In essence, what is needed may be termed a "closed system" in that design should specify what is needed and the end result obtained should dictate future design. A system is needed where "what we got" is recycled back to "what we want," and "what we want" is revised in accordance with performance and the "what we got" data. This is the basic need of a highway department in the area of quality assurance.

Inasmuch as the concepts presented within this report depend on a mutual understanding of certain terms used, the following definitions are provided:

Product Quality—The characteristics of the product that are required for its intended use, including desired levels of these characteristics and allowable tolerance.

Quality Control—All activities and considerations during the manufacture of the product which are necessary to ensure that the product has the desired quality characteristics, both levels and tolerances.

Acceptance Sampling and Testing—The collection and testing of samples of the product and/or the inspection of the manufacturing process as required to determine if the quality characteristics of the delivered product conform to the required levels and tolerances.

Quality Assurance—The actions and considerations included in both "Quality Control" and "Acceptance Sampling and Testing."

Quality assurance and acceptance procedures currently used by the highway industry need to be critically reviewed and assessed for adequacy. Much of the basic technology, concepts, and some data required are presently available. The need is to assimilate the contributing factors and devise a suitable systems approach.

In appraising the entire system, differing viewpoints will undoubtedly be encountered, particularly in the beginning of such an undertaking. It is possible to predict that at least 3 general classifications of opinion will be encountered, namely, (a) those who feel that the entire system must be excised and replaced with new concepts, (b) those who hold that an orderly evolution toward more effective methods must occur, and (c) those who feel that little or no change is necessary in the existing system. It is predicted that the most prevalent opinion would fall in the second category. If this is the case, how can the evolutionary process be hastened?

It should be apparent that the envisioned system of quality assurance affects all areas of a highway department and not just materials inspection to which it is often limited in current thinking.

The entire cycle of quality assurance affects design, construction, and maintenance. Improved design depends on feedback from construction and from maintenance. Information provided by maintenance can keep the designer informed on the effectiveness of his design and the correctness of his assumptions. Information from construction can aid the designer in establishing specifications that are workable in a realistic sense.

The utopian goals and needs have been defined in the most general terms. What has been so simply stated is, in reality, more complex than might appear. To reach these goals, changes are necessary in the quality assurance process as it interacts between the parties engaged in the engineering endeavor. These changes will affect three major areas, namely, specifications, standardization, and information-handling systems.

## SPECIFICATIONS

Specifications must be written in such a manner that there will be reasonable assurance that materials or construction items of acceptable quality are not rejected—otherwise, the result would be eventual increased bid prices—and that material of inferior quality is not often accepted with consequent future excessive maintenance costs. To be practical, specifications must contain realistic and workable for each characteristic measured. To set realistic tolerances, it is necessary to have intimate knowledge of the factors contributing to variation in the observations. The engineering consequences of exceeding such tolerances must also be evaluated. The mathematician who is adept at classifying the variances may inadvertently do a great service by goading the engineer into reassessing the consequences of apparent infractions of the specifications. These consequences may not always be as serious as supposed.

Specifications must be worded in a manner that the required properties are clearly outlined so that, ideally, only one interpretation can be made concerning the intent. Furthermore, action to be taken when specified tolerances are exceeded must be set forth; it is highly probable that there always will be necessity to deal with "gray areas" or borderline cases, necessitating possible acceptance of pay items with equitable reductions in price based on reduced performance potential.

It is probable that the criticality of defects should be classified; one such system is as follows:

1. Critical—This defect will make the product dangerous to use;
2. Major—This defect will seriously impair performance of the item;
3. Minor—This defect may impair performance but not seriously; and
4. Contractual—This defect is likely to have insignificant effect on performance.

In the typical case of manufactured products, specifications should exhibit clear recognition as to which parties are responsible for the formulation and quality of ingredients throughout the chain of events from initial processing of the raw materials to final acceptance in the finished work. Best consumer-producer relations will usually be engendered by postponing entry of the purchaser into the inspection process until as close as possible to completion of the work at which time he should make final "quality assurance" determinations. Earlier control measures are best undertaken by the producer and are designated "quality control." Inspection techniques employed by the two parties may be quite different; for example, a manufacturer of galvanized metal sheet may find it advantageous to use dynamic inspection methods during high-speed progress of the sheet through the mill, whereas the purchaser will use static methods of inspecting finished metal culvert pipe.

Attainment of such ideal inspection schemes as outlined above is often hampered by economic or technological considerations, or a combination of both. For example, postponing all final "quality assurance" inspection of concrete until it is hardened in place is not feasible because of the often tedious tests now available for such inspection and the inordinate economic consequences if serious deficiencies are discovered.

The contractor or materials supplier needs a strong quality control group responsible for the control of the process on a day-to-day basis and with sufficient management support to make the entire organization quality conscious. Acceptance testing undertaken by a highway agency, on the other hand, might be described as a final check on the efficiency of the contractor's quality control program.

Finally, it might be well to consider a positive incentive in the form of bonuses for superior quality if the latter could be demonstrated to yield better performance, longer service, or have other advantages.

## LABORATORY (TESTS AND TEST METHOD) STANDARDIZATION

Realizing that the future will bring an ever-increasing expansion of contractor and supplier quality control facilities, it becomes evident that a between-laboratory standardization program will be required. Currently, highway departments rely on the Cement and Concrete Reference Laboratory and the AASHO Materials Reference laboratory of the National Bureau of Standards for checks in this area. However, as contractors and producers tend to do more of their own testing, more conflict can be anticipated when test results of control samples do not agree with those obtained for acceptance sampling. A standardization procedure consists of 2 parts. First, a laboratory must be able to demonstrate that it is in control within itself, that it is reproducing tests with a specified accuracy. The second part of the standardization program is to provide a service that will extend the standardization between laboratories, including the supplier, producer, and consumer. The first part of the standardization program can be carried on within a laboratory on a monthly, weekly, or daily basis depending on the need. The second part of the program, while necessary, is not a substitute for the first. Standardization between laboratories is a slow process and can only take place on an annual, or at best, semiannual basis. Nevertheless, it serves a function of pointing up operational differences and nonstandard equipment. A means must be found that will extend standardization services to all laboratories involved, including supplier, producer, and consumer. As contractors assume more of their rightful responsibility for quality control testing, it becomes imperative that test methods contain definite statements of repeatability and reproducibility that are achievable under practical field conditions. The tests should be rapid and reliable and be capable of evaluating both the individual components and the end product. In every case, all parties must use a common yardstick for measurement.

## INFORMATION-HANDLING SYSTEMS

Someone has recently noted that each civilization turns its excess energy to the development of large edifices with which to enshrine itself for posterity. As examples, the Egyptians built pyramids, the Greeks large statues, and medieval Europe large churches and cathedrals. In this line of thought, it has been noted that perhaps the Western Civilization of the twentieth century is destined to build for itself a mountain of paper. Perhaps this is more truth than jest. With this sobering thought in mind, it might be well to look at the highway industry and determine where it stands on this so-called mountain of paper. Further, this should provide motivation to look at the highway industry's future direction on this mountain. Will the mountain be allowed to rule the highway program? Or will industry become its master and landscape it to be the servant without enlarging its size?

To evaluate the future in this area, the past, current, and future status in the field of information storage, retrieval, analysis, and transmission must be examined.

The term "information storage and retrieval" can encompass many facilities. At the mention of this term the mind might envision any number of different things—from a stack of correspondence placed on a shelf in a random manner to the most sophisticated of electronic systems capable of transcribing, electronically, entire texts on an area the size of a pinhead. Analogous statements concerning information transmission or information analysis can readily be imagined. The truth is that most of the industry is operating with systems that are somewhere between the extremes.

It is generally recognized that the orderly and efficient function of the typical highway department, which is aimed toward providing a modern highway transportation system, requires the interplay and interdependence of all the department's separate sections. This interplay is provided by the transmission, storage, retrieval, and analysis of information. Notwithstanding the criticality of this dependence, systems of information storage, transmission, retrieval, and analysis developed in the typical highway department over the past years have, with few exceptions, been only those of immediate daily necessity. To put it another way, it might be said that developments have progressed only a small portion of the way necessary for a completely adequate, integrated system.

It is probably safe to assume that the typical highway department's quality assurance program generates a large amount of data or information. The current and future usefulness of this information involves its analysis and dissemination to the user and its storage as a retrievable record throughout the required retention period.

Although the systems currently in use may be satisfactory for the immediate present, it can logically be predicted that more efficient methods will be required in the near future if available technology is to be used effectively. Then it may well be asked, "On what grounds is such a prediction made? Why the desire to change from the present system? Has it not been stated that current systems are meeting the necessary day-to-day demands? Then why speak of going to a new or different system?" The answer is progress—progress in the area of improving planning, designs, specifications, construction, maintenance, operation of the highway system, and thereby service to the traveling public.

More specifically, the need for rapid analysis and dissemination of information necessary for the evaluation of quality during a construction sequence is certainly self-evident. The need for long-term storage, retrievability, and analysis of information for subsequent performance and cost-effectiveness evaluations, material selections, and other studies should be equally evident.

To accomplish such objectives within reasonable economic boundaries will require development of a totally integrated system for the storage, retrieval, analysis, and transmission of information. Such a system could be capable of maintaining in a small amount of space all needed information for many projects and items over a long period of time. Thus, it may be feasible to enter perhaps 10 or 20 years of operating characteristics under the same file reference as the original design and construction data. Such information should be accessible at any time. From this could stem the development of truly comprehensive criteria based on the mathematical correlation of all phases of highway transportation technology with the performance data. To maximize the use of the data acquired in such a system, it is probable that in the terms of equipment and hardware a more than modest automatic data processing, storage, and retrieval system, coupled with maintenance and performance feedback systems, must be used.

This procedure, while the most desirable, has not been feasible in the past inasmuch as neither the equipment nor the technology were available. Today they are.

The use of mechanized-electronic information storage, retrieval, analysis, and transmission systems has come of age in many industries. It has been noted (2) in other industries that "The cost premium on useful knowledge means that investment in mechanizing our information today is mandatory, because traditional methods have proved inadequate."

To make use of the expanding technology in highway construction it is necessary to apply the same farsighted planning in this field. The future thinking involving information use must therefore be directed toward a system that uses the advanced methods of electronic data processing. There must, then, be envisioned a system that would eventually provide for totally integrated information storage, retrieval, analysis, and transmission that could be controlled, evaluated, and processed by electronic computer. The establishment of a totally integrated system would create a "systems dependent" industry. However, such an approach may very well be necessary if the required efficiency is to be maintained in the future.

It is, of course, possible to continue at great length with additional detail concerning the foregoing, such as desirable goals, feasible alternates, necessary subsystems, etc. However, there are probably as many different variations and workable modifications to a master system as there are interested parties in the use of same. One, therefore, arrives full circle back to our original question. Recognizing that a multitude of differing opinions may exist, many of them based on extensive research in the areas of quality assurance, how can any needed evolution of quality assurance and acceptance procedures in the highway industry be best promoted and supported? Although the risk of oversimplification must be recognized, the answer can be stated very briefly. Any such evolution will, of necessity, require the support of top management in the highway departments and the industry. This segment of management will inevitably base decisions on the cost-effectiveness of quality assurance programs. It would, therefore, appear that "what we need" is a proverbial magic box that could tell what the cost-effectiveness would be in any of the many quality assurance programs that might be proposed when said programs were applied to any of the wide varieties of highway construction projects.

Because access to such a magic box or other means of instant solution is unlikely, it is felt that the key to the entire array of problems could be obtained by development of a model for optimization of the cost-effectiveness of quality assurance programs for highway projects by the use of statistical decision theory.

A very simplified overview of the problem can be stated as follows:

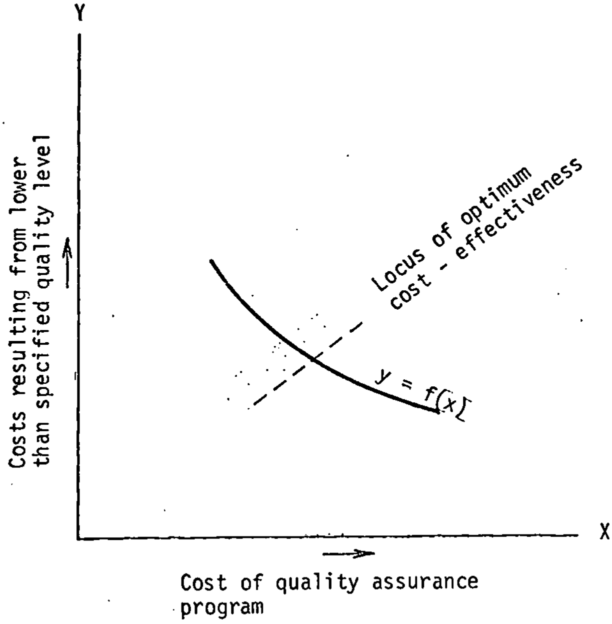


Figure 1.

1. There are typical highway projects of many sizes and types with many complex conditions involved. These should, however, be amenable to mathematical modeling.

2. There are many specifications that could be used. Whatever specification is to be used can be mathematically modeled.

3. There are quality assurance programs with many variations and modifications: some practical, some theoretical, some previously used, others untried. All can be mathematically modeled.

Once this is done, a grossly simplified picture of cost-effectiveness might be envisioned by plotting the cost of increasingly poorer quality versus the cost of increasingly larger and more complex quality assurance programs. One might assume that such a function for a given circumstance might resemble that shown in Figure 1. It can, therefore, be easily seen that if the scales were equal on both axes, the optimum cost-effectiveness would be achieved by a quality assurance program that yielded the level of quality indicated in the intersection of the 2 lines. The actual development of such a model is, of course, of considerable complexity and would require a substantial research effort to accomplish. Such a model suitable for computer utilization should (a) enable simulation of a typical highway construction project of any size and type; (b) generate on demand, by use of statistical decision theory, the cost-effectiveness of a given quality assurance plan for the type of project specified; and (c) generate on demand, by the same methods, the optimum quality assurance plan for a given type of project.

The final report from such a research project should include a complete computer software package for use of the model. Development of such a package would be a major undertaking and would necessitate coordination by a national organization such as the Highway Research Board. This package could then be made available through HRB to all interested parties.

## SUMMARY

Quality assurance must be a common effort, requiring cooperation of the supplier-contractor industry and all sections in a highway department, from advanced planning to operations, to provide a system that most economically produces acceptable highways.

Specifications must be realistic, economically controllable, and must clearly define the responsibility of the contractor and the owner in the area of quality assurance and acceptance.

Maximum usefulness of data derived by different testing facilities can only be achieved if standardization services are available to and used by all facilities involved.

Data derived during the course of a project must be quickly and accurately analyzed. Data from completed projects must be immediately fed back to the interested parties for consideration and utilization on future projects.

Management subjects must be considered. Cost benefits, availability, and training of manpower, communications, and other factors must be recognized and suitably provided for.

Realization of these goals will require coordination of major research and development efforts to evaluate present systems and to devise systems that optimize the cost-effectiveness of quality assurance programs.

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