INTERIM REPORT

THE QUEST FOR PERFORMANCE-RELATED SPECIFICATIONS FOR HYDRAULIC CEMENT CONCRETE

by

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(The opinions, findings, and conclusions expressed in this report are those of the author and not necessarily those of the sponsoring agencies.)

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ABSTRACT

This paper reviews some of the problems associated with quality assurance for hydraulic cement concrete and the difficulties of relating the results of quality control and acceptance testing to the performance of the concrete facility. The importance of good control procedures and inspection of concrete placement by persons knowledgeable in concrete technology is stressed. Also, it is concluded that acceptance procedures based on statistical probabilities are a first step towards attaining the ultimate goal of specification requirements optimally related to performance.

The major problem in this area is identified as one of obtaining sufficient test data to establish an acceptable degree of confidence that the quality of the concrete is as indicated by probability theory. Because of the time and expense of most acceptance tests, particularly strength tests, decisions must be based on limited data.

The report summarizes the specifications of other agencies utilizing statistical probabilities and the recommendations of the American Concrete Institute concerning acceptable strengths. Finally, an evaluation is made of the technique most applicable to the Virginia Department of Highways and Transportation, and specific recommendations are made for changes in the Department's specifications. It is recommended that the revised specification be evaluated by simulated applications to several construction projects.

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INTRODUCTION

A universal goal of the entire highway community is to establish specifications directly related to the capabilities of the highway facility to provide the expected level of service to the community. Associated with this goal is the need to establish an efficient system for quality control, inspection, and acceptance testing that assures the state or other purchasers that suppliers are complying with the construction and material specifications. Over the past 15 to 20 years efforts to meet this need have been centered around the development of test methods more directly related to performance. There has also been substantial efforts to make use of statistical probabilities as means for establishing a reasonable assurance of compliance to specifications without requiring excessive and costly testing programs.

In the case of hydraulic cement concretes, considerable knowledge has been developed concerning those attributes that characterize a high-quality product, and tests are available to measure desirable properties. However, there are unique problems that create the need for special considerations with respect to quality assurance procedures in this technology.

One of the difficulties is that the properties needed for the proper performance of hydraulic cement concrete — for example, strength and resistance to abrasion of the surface — don't exist at the time concrete is placed, and consequently quality assurance must be based on predictive tests and assumptions that the desired properties will develop in a normal fashion. A second problem is that both the manner in which the concrete is placed (consolidated) and cured and the manner in which the test specimens are handled affect the outcome of tests. Improper handling and curing of test specimens can indicate a lack of compliance when in reality the concrete is satisfactory. Conversely, improper placement or curing of the concrete in the job may create deficiencies when the test specimens are satisfactory. A third problem that sometimes creates difficulty is an inverse interaction between desirable properties. For example, a proper degree of entrained air is a necessity for good durability when the concrete is exposed to cycles of freezing and thawing, but such air voids adversely affect strength. Proper workability is required for proper placement, and workability can be improved by the addition of water to the plastic mix. However, an increase in the water-cement ratio can result in low-strength material, as well as a high degree of porosity and low resistance to penetration of deicing salts that leads to corrosion of reinforcing bars and subsequent spalling. Also, different combinations of ingredients can result in different rates of strength development, so that for different mix designs strength determinations at early ages do not always represent the same relation to the ultimate strengths.

These considerations make it essential that for good results hydraulic cement concrete be proportioned by persons knowledgeable in concrete technology, and that its placement be supervised by someone capable of exercising a high degree of on-the-spot judgement. The proper application of statistical techniques utilizing probability principles provides a sound evaluation of available test data, but no specific knowledge is attained concerning the possibilities just discussed that test data based on cylinders or other fabricated test specimens may not accurately indicate the actual characteristics of the hardened concrete in the pavement structure. This same uncertainty exists regardless of how much test data are available or how they may be analyzed. Consequently, agencies are reluctant to base acceptance requirements on statistical calculations derived from test specimens; they feel that the uncertainty would hinder the exercise of proper judgement concerning potential deficiencies in the test specimens themselves or in the procedures for placing the concrete. While these agencies tend to reject applications of statistical principles as a basis for judging concrete quality, others who support the use of statistical probabilities point out that even correct judgement decisions do not provide numerical records of compliance or noncompliance to specifications. In the event a judgement decision is questioned, the lack of specific documentation hinders an equitable settlement of the dispute.

Improvements in the specifications for portland cement concrete for highway facilities can be achieved through a middle-of-the-road approach. Careful quality control and proper placement procedures are needed in all cases. Both workmen and supervisors must be knowledgeable in concrete technology, and they must recognize problems that may require on-the-spot decisions for modifications of acceptance procedures. It is important that a system of acceptance testing be adopted that will provide good reliability at a reasonable cost and risk of making a wrong decision. It is also important that a proper degree of flexibility be built into the system to permit sound engineering judgement to be exercised in all cases.

The specifications and quality assurance in use by the Virginia Department of Highways and Transportation generally provide good concrete. However, problems can arise with materials of marginal quality or when there are combinations of unusual circumstances. Thus, the first step towards improving quality assurance entails the updating or remodeling of the present specifications rather than the adoption of a completely new system. Many of the old requirements should be retained, but principles of statistical evaluation should be adopted to provide standard procedures for resolving difficulties as well as a record of the as-built condition of the concrete facility. Such data would also serve as a base for performance evaluations. There should also be a clear distinction between the quality control procedures that are the responsibility of the contractor or concrete producer and the acceptance testing to be conducted by the Department.

BASIS FOR CHANGING SPECIFICATIONS

Four principles should serve as guidelines to changes. These are:

1. The quality control and acceptance data should be such that the variability and average of measured characteristics, as well as compliance or noncompliance with the specification, can be determined.

2. The remodeled system should be such that contractors and concrete producers with good quality control will have an inherent advantage over those with poor quality control.

3. A system of partial payments for nonconforming concrete should be included, so that when the deviations are small and the cost and inconvenience of tearing out the material outweigh the advantages to be gained by removal, the contractor is subjected to a loss comparable to his responsibility for such failures. This approach would provide an incentive for the contractor to improve his quality control procedures and to minimize his risk of reduced payments.

4. The remodeled system of control should carefully define quality control as the responsibility of the contractor and acceptance testing as a function of the state. Any necessary increase in the amount of testing and inspection performed by state personnel should be held to a minimum.

PREREQUISITES FOR STATISTICAL APPLICATIONS

Present requirements in the Department specifications are generally based on the concept of representative sampling. Judgement concerning compliance is based on a single determination or on the average of two or more determinations. This procedure does not provide information on the amount of variability in the product. As a first step, therefore, it is necessary that certain concepts be recognized as prerequisites for the application of statistical concepts. These are:

1. All materials used in highway construction have an inherent variability. In heterogeneous systems such as portland cement concrete this variability exists within a batch as well as from batch to batch. While a good concrete technologist may be able to detect greater than normal variability by the behavior of plastic concrete, the only way that quantitative estimates of the variability can be made is by the application of statistical principles. The theories of probability and distributions of data from populations of numbers or things are tools that, when properly applied, reveal specific relationships about a series of tests or numbers that cannot be determined by intuition. The use of these tools, however, does not rule out the proper exercise of judgement and actions or decisions related to it.

2. If probability principles are to be employed as a basis for decisions, the samples to be used in establishing the statistical probabilities must be taken randomly. When samples have been taken randomly, the results can be assumed to have a normal distribution, and the inferences drawn from the characteristics of the normal distribution curve and the laws of probability can be used as the basis for specifications, quality control, and acceptance.

The inherent variability in characteristics of concrete from different batches and even in different portions of the same batch is universally recognized, and the specification requirements for measured characteristics generally include tolerances around the desired values. Many of these tolerances have been intuitively derived and are based on a knowledge of normal concrete behavior. Generally, the tolerances for measurable characteristics such as slump and air content are realistic and pose no great problem when applying statistical concepts.

Many of the problems encountered in evaluating the quality of concrete center around strength determinations. For most uses of hydraulic cement concrete, the compressive strength is the major parameter of quality, and it is in this area that the application of statistical principles is most beneficial. When the results of strength tests are significantly less than specified, the probability of poor performance is easily recognized and appropriate courses of action can be established. However, the durability of the concrete is of paramount importance for highway pavements and bridge structures exposed to freezing and thawing and other hostile environmental factors such as deicing salts or sulfate ions from soil or seawater. For concrete exposed to these hostile environments it is necessary to recognize that initial strength levels adequate for supporting all loading conditions may not be indicative of adequate durability.

In order to assure adequate durability, dependence is placed upon the proper design of the concrete mix with respect to the amount of cement and proportions of aggregate and water. Procedures have been devised for measuring the cement content and water-cement ratio of plastic concrete, and a number of these procedures have been shown to be sufficiently accurate for control purposes. However, they usually require expensive equipment and are relatively time consuming; so under the present state of development they are not readily applicable for routine use as quality assurance tools. Consequently, to assure that the concrete specification requirements for the amount of cement and the water-cement ratio are being met, and that placement and curing procedures are being followed, on-the-spot observations of the mixing process and monitoring of the quantities of ingredients used are necessary.

CONTRACTOR QUALITY CONTROL AND STATE ACCEPTANCE PROCEDURES

One of the basic concepts of a statistically oriented specification is that all quality control functions are a responsibility of the contractor and that all acceptance procedures are the responsibility of the state. Present Virginia specifications recognize this division of responsibility, but since the tests for quality control and tests for acceptance are usually the same, many people consider it a waste of time and money to have both the contractor and the state run the same tests on the same concrete. Under present procedures, testing by the contractor tends to be minimized. He is guided by the state's acceptance tests.

Under these circumstances a true end-result specification for hydraulic cement concrete is not possible, nor does it appear feasible at this time to establish such a procedure whereby the state would make acceptance tests only on the finished product. However, ways to motivate contractors to make the necessary control tests and maintain proper control charts should be sought, so that state inspectors could minimize the number of acceptance tests.

Specific instructions to contractors concerning equipment and procedures to be used should be minimized. Contractors should have the opportunity to modify equipment and procedures to reduce production costs, as long as the needed quality is maintained.

One of the best motivations for a contractor to install a good quality control system is to provide a means by which he can reduce production costs or gain other competitive advantages by good control. At first glance it appears that this could be accomplished by using the principles established in the American Concrete Institute recommended practice for judging the acceptability of concrete strength results (ACI 214). How this would apply is discussed in the following section.

STRENGTH CRITERIA

Present Virginia specifications list design requirements for seven classes or subclasses of concrete. The classes are based on a design minimum laboratory compressive strength at 28 days as set forth in Table II-15 of Section 219.10 of the specification. However, Section 411.01 of the Virginia test manual states that concrete is acceptable when 90% of the test specimens meet minimum design strength requirements. While the intent of these provisions is probably understood, the acceptance of 10% of test results below the minimum design strength without further qualification does not provide adequate assurance that a concrete structure will perform satisfactorily.

In practice, and by implication, it is expected that any failure to meet the minimum design strength would be by a small amount. However, unless statistical principles are applied, no quantitative estimate of the likely extremes in strength values can be determined. When statistical probabilities are adopted, specific rules are provided as the basis for defining and judging acceptable material. This approach takes the controversy out of what to do about noncomplying test results.

ACI 214 includes four criteria for judging the acceptability of strength results, all of which are based on statistical concepts. One of these (No. 1) recognizes that design minimum strengths do not, in reality, mean that no part of the concrete has a strength less than the designated minimum (f'_c), but that in practice some percentage of the concrete will be below the limit because of the normal variability in the product. Generally, it is recognized that this can amount to about 10% of the material without serious detrimental effects, provided proper procedures are being followed and only the normally encountered variability is present. This requirement, that only normal variations be present, puts a restriction on the amount of deviation from the minimum requirement that is likely to occur.

It is assumed that the population of test results will have a normal distribution and, accordingly, that the average needed to satisfy a requirement that 90% of the population exceeds a minimum value becomes a function of the variability of the strength test results as indicated by the standard deviation. This is expressed as

$$f_{(cr)} = f'_c + t\,\sigma,$$

where

$f_{(cr)}$ = the average of test results that must be equalled or exceeded in order that not more than 10% of the strength values will fall below f'_c, assuming a normal distribution;

f'_c = the minimum design strength of the concrete;

t = the characteristic of the curve which determines the defective level (the value for 10% defective is 1.28); and

σ = the standard deviation for the population of strength values based on 30 or more degrees of freedom.

This concept is schematically pictured in Figure 1. The curve shown is the normal distribution curve applied to strength results for a particular amount of concrete (population). The vertical axis represents the frequency of occurrence of strength results assuming that every portion of the concrete could be tested (which, of course, is not possible). The shaded area of the curve represents 10% of the area under the curve. Thus, it

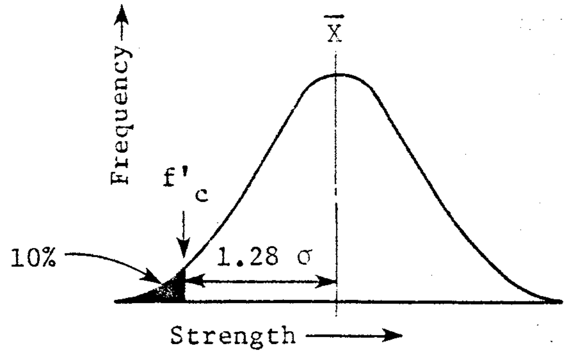

Figure 1. Schematic representation of population characteristics.

is stated that 90% of the population exceeds the strength value indicated, f'_c. In order that this condition be met, the average of all the results, $\overline{X}$, must exceed f'_c by 1.28 times the standard deviation, σ.

To detect trends that would indicate changes in the materials or processes during production, ACI 214 includes additional criteria. One of these is a certain probability that an average of n consecutive strength tests will not fall below f'_c. The usual requirement is that the average of three consecutive tests will not fall below f'_c more than 1 time in 100. This is calculated as

$$f_{(cr)} = f'_c + \frac{t\,\sigma}{\sqrt{n}},$$

where

$f_{(cr)}$, f'_c, and σ are all as previously defined;

t is equal to 2.33 in this case, since the probability of failure to comply is set at 1 in 100 instead of 1 in 10; and

n is the number of averages used in the analysis (n is equal to 3 in this case).

Another criterion given by ACI 214 is that there is less than a 1% chance that any single test result will fall below f'_c by more than a certain amount. This is usually set at 500 psi.* Thus,

$$f_{(cr)} = f'_c - 500 + t\,\sigma,$$

where

t = 2.33 for a probability that a result lower than this will not occur more than 1 time in 100.

Examples showing the average results required to meet these criteria for different situations are given below. For good control, the standard deviation is assumed to be 400 psi; for poor control, it is assumed to be 800 psi.

Assume A-4 concrete, f'_c = 4,000 psi

For good control σ = 400

Criterion 1 $f_{(cr)} = 4{,}000 + 1.28 \times 400 = 4{,}512$

Criterion 2 $f_{(cr)} = 4{,}000 + \frac{2.33\ (400)}{\sqrt{3}} = 4{,}538$

Criterion 3 $f_{(cr)} = 4{,}000 - 500 + 2.33\ (400) = 4{,}432$

For poor control σ = 800

Criterion 1 $f_{(cr)} = 4{,}000 + 1.28 \times 800 = 5{,}024$

Criterion 2 $f_{(cr)} = 4{,}000 + \frac{2.33\ (800)}{\sqrt{3}} = 5{,}076$

Criterion 3 $f_{(cr)} = 4{,}000 - 500 + 2.33\ (800) = 5{,}364$

From these examples it is seen that for the same level of control (same σ), all criteria require about the same average for acceptable concrete. However, when the standard deviations are different the averages for acceptable concrete are significantly different. Under this system, a contractor with poor control having to supply concrete with a higher average than he normally attained under the present system would most likely be required

* See page 19 for factors to comment customary U. S. units to S. I. units.

to use a higher cement factor than he previously used or, alternatively, more expensive aggregates than he previously used. This would place him at a distinct disadvantage in relation to a contractor with good control who could continue to use usual mix designs and materials.

PROBLEMS OF APPLICATION TO HIGHWAY PROJECTS

Unfortunately, there are some difficulties in applying the principles established in ACI 214 directly to many highway projects. First, all of these calculations are based on the assumption that the process is in control; that is, that everyone is doing everything right to the best of their ability. If something goes wrong with the scale, or somebody dumps fly ash instead of cement in a batch, the process is out of control and the assumptions concerning the quality indicated no longer apply. This means that the adoption of statistical procedures does not eliminate the necessity for maintaining constant vigilance during the production process. With reputable firms such as would normally supply material to the state, it would be expected that gross malfunctions would be quickly detected and immediately corrected by contractor personnel, but for good relations and to avoid sloppy practices, a state inspector should be present at a job site for all projects where the quality of the concrete is critical to the performance of the structure or pavement.

Another problem relates to the number of tests needed to provide good estimates of the averages and standard deviations. ACI requires that at least 30 determinations be used for establishing the sample average and standard deviation, because this is the minimum number needed in order that the estimates can be assumed to be essentially equal to the true standard deviation and average of the population.

This amount of data for a single lot, and in many cases even for the total project, is unrealistic with respect to test results on many highway projects, particularly for strength results on portland cement concrete. Consequently, if lot-by-lot acceptance is desired, it is necessary to devise procedures for making decisions with smaller amounts of data. Generally, these conditions dictate that on a statistical basis the state take relatively large potential risks that some noncomplying material will be accepted. Fortunately, the real risks under these circumstances are not as great as would be indicated by statistical principles alone. If a knowledgeable concrete inspector is present, he is able to visually detect, and take immediate action to eliminate, gross problems (excessive slump, high air, etc.) that would cause large deviations in strengths.

Several options, all of which are statistically valid, are available, and the best one to use may depend on the conditions surrounding a given project. The size of the job, the volume of concrete being produced each day, the quality control measures normally followed by the contractor, and the variability of the materials being supplied to a job may all have a bearing. To establish a basis for selecting a suitable option or options for the Virginia Department of Highways and Transportation, the specifications of other state transportation departments utilizing statistical probabilities were reviewed. The results of this review are summarized in the following section.

HIGHLIGHTS OF STATES' STATISTICALLY-BASED SPECIFICATIONS FOR HYDRAULIC CEMENT CONCRETE

The FHWA reports that relatively few states have made extensive use of statistical concepts in their specifications for hydraulic cement concrete. No attempt was made to determine all the states that may have experimentally tried such specifications; however, copies of the specifications in use in 1980 by West Virginia, Louisiana, Georgia, Maryland, and Ohio were obtained and reviewed. In addition, a proposed specification for New Jersey and the Standard Specifications for Construction of Roads and Bridges on Federal Highway Projects (FP-79) were also reviewed. The highlights of these specifications are summarized in Appendix A.

While all these agencies have applied statistical procedures intended to judge the acceptability of the concrete as a whole, for the most part they have applied them in different ways and have used different criteria for acceptance. However, there are some common elements in all the specifications. All of the agencies emphasize that the contractor is responsible for quality control, but they retain considerable descriptive requirements concerning the concrete mixing and placing equipment and details on handling materials. All also require the contractor to have on-the-job supervisory and technical personnel certified in some manner as having good knowledge of concrete technology. All require that the mix design be prepared by the contractor and that it be approved in some manner prior to start of the work. All have minimum and maximum temperatures at which concretes can be placed without special procedures for protecting the concrete in cold weather or cooling it during mixing in hot weather. In general, all of these instructions are basically good concreting practices such as set forth in various recommendations of the American Concrete Institute, and similar descriptions and requirements appear in all state specifications for hydraulic cement concrete, regardless of whether or not statistical procedures for evaluating compliance have been adopted.

The statistical evaluation of strength results is used by all agencies in computing a reduction in payment for noncomplying structural concrete that is left in place. In addition, a factor for noncomplying results for entrained air is used by the FHWA (Region 15). Ohio also uses both air content and strength results in determining partial payments in its specification for base concrete. Differences occur in the manner the variability is taken into account and in the pay factors established for different degrees of noncompliance.

In some cases the range of test results (difference between highest and lowest values) within a lot is used as an estimate of the variability and in others the standard deviation is used. Specifications of this type are referred to as variability unknown. In each case the average value of strength accepted for full compliance is dependent upon the magnitude of the variability indicated by the tests themselves. Thus, where poor control is indicated by a high range or standard deviation, a higher average is required than if good control is indicated by a smaller range or standard deviation. Only Louisiana bases its requirements on average strengths without adjusting for differences in variability. This, in effect, means that Louisiana assumes the variability for all jobs and concrete producers to be the same. This is referred to as a variability known specification.

Twenty-eight day strength results are the basis for all analysis. However, predictions of 28-day strengths based on accelerated curing or early strengths from a prediction curve (maturity concept) are used by some agencies. West Virginia gives the contractor the option of using early strength tests as a means of predicting 28-day strengths using the maturity concept. Georgia uses an accelerated curing procedure for predicting 28-day strengths and will accept concrete on the basis of the predicted strength, but rejections or reductions in payment are based on actual 28-day strengths.

SPECIAL CONSIDERATIONS FOR VIRGINIA CONDITIONS

In deciding which of the available alternatives may be most suitable for modifying the hydraulic cement concrete specifications of the Virginia Department of Highways and Transportation, consideration must be given to the type of construction involved, the size and number of state contracts, and the size and number of producers furnishing concrete to the state.

Type of Construction

At present very few concrete pavements are being constructed in Virginia, thus initial concern is with structural and incidental concrete. The major concern with structural concrete is with that used in bridge decks. While adequate strength is, of course, necessary, the durability of the concrete is of even greater concern because of the severe exposure of decks to deicing salts. For adequate durability, the proper water-cement ratio and the proper amount of entrained air are very important. Unfortunately, as previously discussed, all methods for the direct determination of the water-cement ratio in freshly mixed concrete are somewhat complicated, require expensive equipment, and are time consuming. At the present time it is cost-effective to rely on close control by the concrete producer of the amounts of ingredients added and close inspection by the state to assure compliance for proportions of ingredients. The extreme importance of air content also dictates frequent tests for entrained air.

For structures such as abutments, piers, etc., proper control must be exercised for every placement, because the integrity of the entire structure could be affected by a single lot of poor quality concrete.

Size and Number of Contracts

At present most contracts for supplying portland cement concrete to the Virginia Department of Highways and Transportation are relatively small. Under these circumstances, it is not cost-effective to make sufficient tests to establish a high degree of probability that the indicated results truly represent the total population. Consequently, this situation is not favorable to the efficient application of some statistical procedures.

Table 1 shows the approximate number of contracts of various sizes advertized for bids for each month during 1980 and the first 6 months of 1981. Contracts requiring less than 50 cu. yd. of concrete are not included in this tabulation. Under present specifications, it is customary to make one set of cylinders for strength tests for each 100 cu. yd. of concrete. At this frequency of testing, only 23 of the projects would provide more than 10 strength results. While an estimate of the standard deviation and the average of 10 results can be used to establish a reasonable estimate of the population parameters, at least 30 test results are needed to establish a 95% level of confidence that the estimates truly represent the population. Thus, unless the frequency of testing is increased, procedures for establishing a standard deviation based on pooled data must be employed or, alternatively, for most projects the Department must accept relatively large risks that the concrete could be of lower quality than indicated by the test results.

Table 1

Number and Size of State Contracts
Involving Portland Cement Concrete

	Quantity of Concrete — Cubic Yards					
	50-99	100-299	300-499	500-1,000	1,000	TOTAL
Date	Number of Contracts					
1980						
January	2		1	1		4
February		1		2	2	5
March					1	1
April			2	2		4
May					2	2
June	1	2	3		2	8
July	1	4	4	1	6	16
August					1	1
September	1	4	2		4	11
October	1	3	2	1	2	9
November	2	4	1	4		11
December			2	1	1	4
1981						
January		3			2	5
February	1	2	1	1		5
March		1				1
April		2	2	1		5
May	1			1		2
June		1	2	2		5
TOTAL	10	27	22	17	23	99

Number of Concrete Producers

Essentially all structural concrete is supplied by ready-mix concrete producers. Approximately 110 such producers are qualified to furnish concrete to the state, although the records for 1980 indicate that only 38 producers provided concrete for which strength tests were made. Twenty-two producers supplied both Class A3 and Class A4 concretes, 12 supplied A3 concrete only, and 4 supplied A4 concrete only. Thirty or more strength tests were made for 11 producers of A3 concrete and 10 producers of A4 concrete. Fewer than 10 tests were made on the product of 13 producers of A3 concrete and 5 producers of A4 concrete.

The summary shows that if all projects supplied by a given producer using the same mix design were pooled, the requirements in ACI 214 for at least 30 tests could be met in only a few large jobs and large producers of concrete in Virginia. In these cases, the use of a standard deviation based on a producer's own production as in ACI 214 could be utilized to establish a good statistical estimate of the percentage of concrete above the design strength (f'_c). However, a large proportion of the concrete producers do not have a sufficient volume of production to establish a good estimate of the standard deviation for their products (at the present testing frequency). In these cases it will be necessary to use an assumed standard deviation based on historical records or to estimate the variability from a small number of tests with accompanying high statistical risks of wrong decisions. In the latter case, acceptance criteria can be set high so as to minimize the risk of having poor quality concrete in the job, but economy is sacrificed by requiring the overdesign of the concrete mix.

RECOMMENDATIONS FOR VIRGINIA SPECIFICATIONS

After the review of the various approaches taken by other agencies, it appears that a continuous acceptance plan similar to that now being used as special provisions by Region 15 of the FHWA might be suitable for the size and type of concrete construction required by the Virginia Department of Highways and Transportation. Theoretically, from a statistical standpoint the maintenance of a 5% producer's risk of rejecting good material as is done in the Region 15 procedure results in a relatively large risk of accepting material of slightly less than the indicated quality on small jobs, but good inspection should visually detect grossly defective concrete and prevent its use.

It is noted that the same risks of accepting poor materials are inherent in the present procedures. Thus, the possibility of inadequate performance would be no greater than now exists. For large jobs, the state's statistical risk is reduced significantly, because the total concrete is considered a single lot and all valid values are included in the analysis of overall concrete quality. It is emphasized that this approach is based on a continual application of good control procedures during the entire job. Situations involving obviously bad concrete must be corrected as they occur, and such bad concrete must be removed from the job.

Appendix B is a suggested revision of Section 219 of the Virginia Department of Highways and Transportation Road and Bridge Specifications to incorporate the statistical features of continuous acceptance for portland cement concrete. It is recommended that this revision be reviewed by the Materials and Construction Divisions, and that after preliminary revision it be evaluated by using it on selected projects as a supplement to present procedures, without actual implementation of the reduced payment schedule when the concrete is acceptable under present procedures.

Significant aspects of the recommended revised specifications are as follows:

1. The descriptive material concerning equipment and procedures is unchanged for the present, although some of the detailed instructions probably should ultimately be deleted to provide the contractor more flexibility. While a simple reference to ASTM Specification for Ready-Mixed Concrete (C-94) does not appear feasible, the requirements in Section 219 should be compatible with the ASTM specification to the extent possible. Concrete for highway construction represents only a small percentage of the volume of business for most ready-mix concrete producers, thus significantly more restrictive plant requirements would most likely be unenforceable.

2. The present revision does not require a submission of a detailed quality control procedure by the contractor as is done by the FHWA. However, subsequent action for this requirement may be desirable. Should this occur, guidelines would be prepared by the state.

3. The revised Sections 219.10 through 219.14 establish a statistical acceptance for air content and strength results for all classes of structural concrete and a reduced payment factor to be used if deficiencies in either property are indicated.

A suggested frequency of testing based on the total size of the structure or project is included. The proposed schedule would probably increase slightly the amount of testing for small jobs, but would require about the same rate as now for large jobs. Some method for randomizing when samples are to be taken would be a requirement for these tests. Under the new specification, acceptance would be based on the average 28-day strengths of a set of three 4-in. x 8-in. specimens. Strength tests at 14 days, if made, would be only by the concrete producer or contractor for his information.

Acceptance on the basis of predicted 28-day strengths obtained by accelerated curing or the maturity concept is a goal for the future, but further research is needed before a recommendation can be made.

The revised section requires more stringent testing for air content on concrete bridge decks than for incidental concrete. For bridge decks, the first 3 loads are tested, and when these are in compliance, one randomized sample for each subsequent group of 5 batches is taken (not one for every fifth load). Should a failing test result be obtained, each subsequent load would be tested until 3 consecutive tests were in compliance. All out-of-specification material would be rejected. Final acceptance and the pay factor would be based on the acceptance samples only. For randomly selected incidental concrete, after the initial sample is shown to be satisfactory, the air content would be determined only on the results of tests on randomly selected acceptance samples, and final acceptance and pay factors would be based on the statistical analysis of those results.

The final acceptance of concrete is based on a statistical analysis of air content and strength results. Except for very large jobs, the total concrete of a single class in a contract would be treated as a single lot. A reduced payment would occur when the analysis showed that with a producer's risk of 5%, more than 10% of all the production of a given mix did not meet the requirements for compressive strength (f'_c) and air content. The quality level is determined from a table of normal distributions indicating the percentage above the limit using the standard deviation of all valid tests made for the project. This quality level is determined after applying a correction factor to the indicated average so that the producer's risk is reduced to 5%. If adopted, the details of how to determine the indicated quality level would be spelled out in a special Virginia Test Method to be placed in the test manual. The proposed text for such a method is included as Appendix C.

Except for testing at 28 days instead of 14 days, it is believed that adoption of the proposed revisions would not greatly change the present procedures. For situations where all present specifications are being met, the quality of the concrete being placed is not likely to change; however, the revisions would establish a situation in which contractors with borderline materials producing concrete with minor deficiencies could be penalized if the strength of their concrete was lower than specified. Such concrete is now accepted by the Department at full price. The revisions would also spell out how much is to be paid for any such concrete left in place. Reduction of cement factors by producers would not be permitted under this modification, but good control would pay off by establishing a lower average that must be met for 100% payment.

A further significant advantage would be a better knowledge of the as-built characteristics of the concrete that would provide a data base for subsequent performance evaluations.

Conversion to SI Units

Pounds per square inch (psi)	x	6.895	=	kilopascal (kPa)
Cubic yard (yd^3)	x	0.7645	=	cubic metre (m^3)
Square yard (yd^2)	x	0.8361	=	square metre (m^2)
Pounds per cubic yard (lb/yd^3)	x	0.5933	=	kilograms per cubic metre (kg/m^3)
Inch (in.)	x	0.0254	=	metre (m)
	x	25.4	=	millimeter

A 4 in. x 8 in. cylinder is nominally equivalent to 100 mm x 200 mm.

A 6 in. x 12 in. cylinder is nominally equivalent to 150 mm x 300 mm.

APPENDIX A

HIGHLIGHTS OF STATISTICAL-BASED SPECIFICATIONS FOR HYDRAULIC CEMENT CONCRETE

FEDERAL HIGHWAY PROJECTS (FP-79)

Structural Concrete

The specification establishes the minimum cement content, maximum water-cement ratio, and range of air content.

The minimum strength for each class of concrete is specified on project plans.

The contractor designs the mix for each class he will use on a project and makes all subsequent adjustments.

The contractor submits one or more mix designs at different water-cement ratios. The design air content and slump are to be at the midpoint of the specification band.

The contractor must submit 28-day test results on trial mixes at least 30 days before starting the job.

Any change in concrete mix design must be approved by the engineer.

The contractor submits his quality control plan at a preconstruction conference.

The plan must include detail procedures concerning the type and frequency of sampling and testing. It must also include process control procedures for measuring, mixing, and delivery of concrete, procedures for washing out delivery trucks and other equipment, aggregate moisture control, hot and cold weather concreting, slump, air, temperature, and strength testing.

The engineer shall be provided access to plant production records and, if requested, copies of certifications and test reports for the ingredient materials.

The contractor must provide experienced and qualified personnel. The contractor's personnel perform all sampling, testing, and inspection necessary to assure quality control.

The contractor certifies in writing that his concrete production facilities are in conformity with State Highway Standards or those of the NRMCA, Plant Certification Program, or others.

The contractor keeps records of the nature and number of observations made, including number and type of deficiencies found, the quantities approved and rejected and the nature of any corrective action taken.

Acceptance Sampling and Testing

Acceptance sampling and testing are performed by the engineer. The contractor furnishes all materials to be tested to the engineer. The engineer may designate one or more of the contractor's quality control tests as an acceptance test. The procedures used are as follows:

Air Content and Slump:

Use 100% sampling at the start of each day's production.

When 3 consecutive samples meet the specifications, change to random testing of 1 for every 5 successive batches. Go back to 100% testing if any failure occurs.

Use T152 and T196 as appropriate for air content. T199 (Chace air indicator) may be used for acceptance but not rejection. Determine slump by T119. Slump acceptance but not rejection may be visually determined by engineer.

Determine water-cement ratio from weight buckets.

If tests show a high water-cement ratio or a low cement content, reject and remove the concrete from the job site.

The time from batching to discharge of the concrete shall not exceed 1 hour. Additional 1/2 hour is allowed if retarder is used.

Compressive Strength

Lots are accepted on the basis of the mean and range of acceptance test results.

Three, 4, or 5 acceptance samples, 2 cylinders each, are selected randomly from each lot, depending on the size of the lot.

If no test result is below f'_c, accept the lot.

If any test result is below f'_c, use the table for the pay factor (P.F.) to be applied.

P.F. = 1.00 — when strength equals or exceeds $f'_c + aR$

P.F. = 0.95 — when strength equals or exceeds $f'_c + bR$

P.F. = 0.85 — when strength equals or exceeds $f'_c + cR$

P.F. = 0.70 — when strength is less than $f'_c + cR$,

where

R = difference between smallest and largest strength value for each lot (range); and

f'_c = minimum 28-day compressive strength specified on plans.

For 3 sample lot	a = 0.18	b = -0.07	c = -0.30
4 sample lot	a = 0.20	b = 0.01	c = -0.16
5 sample lot	a = 0.21	b = 0.21	c = -0.10

For small lots of less than 3 samples, the engineer will evaluate as follows:

If the sample from single batch fails to attain f'_c, the engineer will determine what detrimental effects are likely. He may require removal of the concrete or accept it in accordance with the following schedule

1.00 P.F. — average strength = 0.98 f'_c or greater

0.95 P.F. — average strength less than 0.98 f'_c but .96 f'_c or more

0.85 P.F. — average strength less than 0.96 f'_c but .94 f'_c or more.

0.70 P.F. — average strength is less than 0.94 f'_c

Batches not sampled are evaluated by the engineer and accepted or rejected on the basis of judgement.

FHWA REGION 15, SPECIAL PROVISIONS TO FP-79

Region 15 of the FHWA is the agency that has the responsibility for constructing roads in National Parks and for federal agencies in the eastern part of the United States. It has modified, on a trial basis, the quality assurance procedures for portland cement concrete included in FP-79. The modifications provide for continuous acceptance of structural concrete. The special provisions state that the acceptance plan will accomplish the following.

"1. Reduce testing (from that required by present FP-79), particularly on small quantity placement operations.

2. Better define and enhance contractor responsibility for quality control.

3. Improve contract administration by eliminating the 'zero defects' clauses in FP-79 for slump, air content, and water-cement ratio by adding a statistically based acceptance plan for air content.

4. Improve contract administration by improving the accuracy of quality level assessments and eliminating minor penalties for insignificant deficiencies."

Under the continuous acceptance plan all concrete production of the same class and design strength is treated as one lot. During the course of the work the contractor is advised of available acceptance test results and is given a projected pay factor on the basis of continuing the same quality level of production. It is conceivable that for larger jobs a contractor starting out with a projected pay factor less than 1.00 could improve production to the degree that the final factor is 1.00.

The following are the major steps necessary to implement continuous acceptance of portland cement concrete at the construction project level.

1. A special Random Interval Sample Selection (Concrete) Form is completed prior to the start of production. This information remains confidential so that the principle of randomness is preserved and the sampling is unbiased. The contractor is not aware of which batches will be sampled until the time for sampling arrives.

2. At the start of production, screening tests are made to verify that air content, slump, temperature, and water-cement ratio (verified from ticket) are within specifications. The contractor furnishes the technician for these tests, but the engineer gives guidance as needed to assure that the tests are performed properly.

3. The engineer has the discretion to test any load and to reject all nonspecification concrete, whether or not a partial load has been placed or whether or not such a load was to be tested for the statistical analysis of test results. Test results on such especially tested or rejected loads are not included in the final evaluation of the quality level.

4. The engineer maintains a cumulative concrete log and when a sampling point as indicated in step 1 is reached, samples are taken and tested in accordance with the contract provisions.

5. All test results on randomly selected samples are entered on computation sheets as they become available. A test result for strength is the average of 2 cylinders at 28 days. The range between the individual values must be less than 10% of the average strength or the test results are not valid.

   The average and standard deviation are calculated from all test results to date. A producer's risk correction (Cpr) is applied to the average of the test results so that there is a 95% certainty that the true quality level is no higher than that indicated and a reduction in pay factor is warranted. (This is a producer's risk of 5% that material at the acceptable quality level may be rejected.)

   The equation for the producer's risk correction is

$$C_{PR} = \frac{(1.65\ s)}{\sqrt{T}},$$

   where s = standard deviation, and

   T = estimated final total number of samples. T may be corrected periodically until the final number of samples (N) is known.

The producer's risk correction (C_{pr}) is then added to the average of the test results and the corrected average, $\overline{X}_c$, is used to determine the "z" factor to be used as the basis for establishing the indicated quality level from normal distribution tables. The equations are

$$\overline{X}_c = \overline{x} + C_{pr} \quad \text{and}$$

$$z = \frac{\overline{X}_c - LL}{\sigma},$$

where

$\overline{x}$ = actual average of test results,

C_{pr} = producer's risk correction,

$\overline{X}_c$ = corrected average,

z = factor for determining quality level from normal distribution table,

LL = lower specification limit, and

σ = standard deviation.

The indicated quality level is then corrected to give the contractor credit for defective concrete which is theoretically considered in the computed quality level but is not incorporated in the work. The correction applied is the percentage of the total concrete delivered to the job site that was rejected.

6. Compute the projected pay factor and advise the contractor of results at least once a week when the project pay factor is less than 1.00 or once a month when equal to or more than 1.00.

7. Compute the final pay factor on the basis of the overall average and the standard deviation of all valid tests for strength and air content.

When the results of air content tests indicate, with a producer's risk of 5%, that less than 90% of all production meets the specification requirements, then a reduced pay factor (RP_a) will be applied. This is computed as

$$RP_a = \frac{QL_a + 10}{100},$$

where

RP_a = reduced pay factor for air, and

QL_a = quality level for air (percentage meeting specifications).

The reduced pay factor for air content will not be less than 0.70.

If the statistical analysis for all valid 28-day strength data indicates, with a producer's risk of 5%, that less than 90% of all production of a given mix meets the specification requirement for f'_c, then a reduced pay factor will be applied to the concrete portion of all items containing the involved concrete. Such reduced pay factor will be computed as

$$RP_s = \frac{(QL_s + 10)^2}{10,000},$$

where

RP_s = reduced pay factor with respect to 28-day compressive strength (this figure will not be less than 0.70), and

QL_s = quality level for strength (percentage meeting specifications with respect to strength).

In the event that neither air content nor 28-day strength meet the required 90% quality level, then a net reduced pay factor (RP_N) will be computed as

$$RP_N = RP_A \times RP_S.$$

This figure will not be less than 0.70.

RP_N will be projected periodically during the course of production. In the event RP_N is less than 1.00, the progress payments will be reduced accordingly.

If at any time during production RP_N is projected to be at the minimum level (0.70) and the contractor is taking no effective action to improve the deficient quality levels, the engineer may order production stopped until the deficiencies are corrected.

The pay reduction in dollars is computed as follows:

For concrete bid by the unit (cy, etc.)

$PR = C \times Q \times BP \times (L - RP_N)$,

where

PR = price reduction in dollars,

C = a cost factor equal to 0.35 representing the estimated concrete portion of the bid item,

Q = quantity of concrete involved in the same units as the bid price,

BP = bid price per unit, and

RP_N = net reduced pay factor.

For concrete included in a lump sum

$PR = C \times Q \times LS \times (1 - RP_N)/T$,

where

T = total quantity of concrete in the item,

LS = lump sum bid price, and

other symbols are same as above.

The contractor submits data on the mix design at least 35 days in advance of starting the job. These tests must be prepared by an approved testing laboratory.

The minimum cement content, maximum water-cement ratio, and range of design air content are established in the specifications for each of 3 classes of concrete.

Classes 1 and 2 are verified for early strength development in accordance with ASTM C-684 Method A (Accelerated Cure).

Flexural Strength

The Design Acceptance Range (DAR) for flexural strengths established for each class is as follows:

Class 1 — DAR = 600 psi + 0.67 s

Class 2 — DAR = 700 psi + 0.50 s

Class HES — 700 psi + 0.50 s

The acceptance limits are based on 9 cured specimens; 3 specimens each from 3 batches.

The standard deviation, s, is determined from all 28-day flexural specimens prepared for a given combination of materials, except that a value of s greater than 37 psi shall not be used.

Compressive Strength

Minimum acceptable compressive strengths, termed a job performance value (JPV), are established as follows:

Class 1 — JPV = 3,000 + 0.18 R

Class 2 — JPV = 3,500 + 0.21 R

HES (High Early Strength) — JPV = 3,000 + 0.05 R

The contractor may adjust proportions of fine and coarse aggregate in his mixes but the cement factor must not be decreased and the water-cement ratio must not be increased.

No concrete is accepted with entrained air less than 2.0% or more than 6.5%.

A lot acceptance plan by variables is used to determine strength acceptability.

Lots are approximately 5,344 $yd.^2$ of concrete placed continuously except for overnight or other minimal discontinuation. Ramps are considered as separate lots. Three production units are randomly selected for strength tests from each lot.

For Class 1 and Class 2 concrete a minimum of 2 sets of 2 cylinders (6 in. x 12 in.) are made for each production unit. One set is cured by ASTM C-684 (Method A) (Accelerated) and one by AASHTO T23 (normal). The minimum average acceptable early strength is the average strength at 24 hours of the laboratory design less 1.5 times the standard deviation of the laboratory design. If the average of 3 lot acceptance tests exceeds the value of the JPV, accept the lot at full contract price and discard the 28-day cylinders. The strength tests for a set of cylinders are not accepted if the range of the results exceeds 35% of the average. When a failing test is obtained, the contractor is notified immediately. He then has the option of removing or leaving the concrete in place pending acceptance or rejection on the basis of 28-day strength test results.

If the concrete is left in place and the 28-day strength is below specifications, the contractor can remove the concrete or accept partial payment as follows:

Pay Factor	L A L
Class 1	
1.00	3,000 + 0.18 R
0.95	3,000 - 0.07 R
0.70	3,000 - 0.30 R
Class 2	
1.00	3,500 + 0.21 R
0.95	3,500 - 0.07 R
0.70	3,500 - 0.30 R

where

LAL is the lower acceptance limit and
R is the range of results.

When the lower acceptance limit for the 0.70 pay factor is not met, the engineer may order removal. If the concrete is left in place, the payment is 50% of contract price.

Paving concrete may be accepted on the basis of 72-hour tests on cylinders cured at conditions under which pavement is cured. The strength must equal or exceed the minimum JPV (3,000 + 0.18 R and 3,500 + 0.21 R, respectively, for Classes 1 and 2).

When the pavement is deficient in thickness as well as strength, the specification combines the deficiencies for establishing the pay factor.

LOUISIANA

General Requirements

Plants are certified by the Department.

Laboratory facilities are furnished by the contractor.

The contractor must have a qualified concrete batcher on the job.

Cement is certified by the manufacturer. If not certified, provisions must be made for storing the cement for 12 days or until the tests are completed.

The mix design is submitted by the contractor for approval. The design must include the source of all materials.

When pretests are required, the mix design must be submitted at least 45 days prior to start of work.

Control Tests

The contractor is responsible for the gradation of coarse and fine aggregate, slump tests, air content, and temperature. The production mix must conform to the mix design within specified control limits for individual samples.

Results are plotted on control charts for individual samples.

For structural concrete, each lot is represented by a minimum of 2 individual tests.

Adjustments to the mix design may be made by the contractor for slump, air, etc. The cement content can exceed the minimum in the mix design with prior notification of the Department.

The average strengths of test cylinders must exceed set minimums. Therefore, all variabilities are considered the same; that is, it is assumed that all producers have the same standard deviation for their product.

The lot size for structural concrete is not to exceed 200 $yd.^3$ If the range is 200-400 $yd.^3$, divide into 2 equal lots. Pours exceeding 400 $yd.^3$ are represented by 3 lots. Take 2 random batches for making cylinders from each lot. Make 3 cylinders for each batch. Test all 6 specimens at 28 days.

MARYLAND

The contractor submits the mix design for approval.

Trial mix testing is required with an authorized representative of the state materials engineer present. These tests must be made at least 28 days prior to job start.

The contractor cures the specimens and delivers them to the Maryland laboratory for tests. The strengths in the trial tests are expected to be about 25% above minimum.

The frequency of testing and responsibility are as follows:

Control tests: Slump: 1 for each 50 yd.^{3} — made by project engineer; air content: 1 per 50 yd.^{3} — made by project engineer.

Compressive strength specimen: 1 per 50 yd.^{3} or as randomized by engineer.

If the first slump or air content test fails, accept or reject the batch on the basis of a second test result.

When average strengths are lower than indicated by the trial mixes, corrective measures are taken. No partial payments are applied. Case-by-case disposition is made of failing tests.

NEW JERSEY

The contractor establishes the mix design.

The mix design is verified by contractor's tests with a state representative present.

For mix design approval, 6 test cylinders are prepared for each trial batch.

The target strength for the design is set at 500 psi above the minimum specification requirements for each class.

Minimum levels of the average for the desired quality are given in the specifications.

Acceptance levels are based on a maximum of 10% defective for all classes of concrete except prestressed, which is set at 5%.

The acceptance formula is

$$\overline{X} = D + Z\ s,$$

where

D = design strength,

Z = 1.645 for 5% defective or
1.282 for 10% defective, and

s = standard deviation.

The standard deviation is established for each contractor on the basis of cylinders tested by the state. The current standard deviation for any contractor is based on the most recent 10 lots or 1 month's production, whichever is the larger sample size. Lots need not be all the same class concrete.

When sufficient data are not available, the standard deviation is set at 1,000 psi until at least 10 lots are available.

For acceptance the lot size is set at 500 cu. yd. or 50 truck-loads, whichever is smaller. Batches (or trucks) are selected randomly.

Structures are taken as 1 lot unless the volume exceeds 1 day's production, 300 $yd.^3$, or 50 truckloads. If the volume of concrete is to be divided, divide into equal lot sizes.

Six samples are normally taken from each lot (n = 6). If n is other than 6, tables for Q_L are provided in the specification.

The pay factor for any lot of concrete is determined by the following formula:

Pay factor = 115 - percent defective.

If the pay factor is greater than 1, credit is given to offset lots with a pay factor less than 1. But the actual payment never exceeds 100% of the bid price.

No retests are made when strength tests on cylinders show 30% or less defective. Payment is made on the basis of the pay factor formula.

When the percent defective for cylinder strengths exceeds 40% (30% prestressed), retest by coring. If low strength is confirmed, concrete may be removed. If left in place, use larger pay factor shown by test but not less than 50%.

When single tests are below the limits set in the specification, retest by coring or by nondestructive means. If retests show low strengths, establish the quantity involved and treat as a separate lot. Evaluate the remainder on basis of other tests.

For slump and air content tests, select batches randomly at the same rate as required for compressive strength tests. While these tests are being made, hold the concrete in the truck or bucket. If tests are within limits, accept the concrete. If tests are outside the limits, make a second test on the same load. If the second test is within limits, accept the concrete. If not, reject and remove load from job site.

The specification allows one adjustment for slump.

If the air content is low, additional air-entraining agent may be added, but if the second test fails, reject the load.

OHIO

Ohio uses a statistical specification for portland cement concrete on bases only.

Its requirements are:

> 3,000 psi minimum strength at 28 days.
>
> Air content 4.0% minimum, except when size 7, 78, or 8 stone is used. In these cases, minimum is 6.0%.

The contractor submits certified test data from a certified laboratory (CCRL inspection is adequate) showing compliance. Changes in material sources must be approved.

Quality control is the responsibility of the contractor. He establishes systems and maintains records of all test results. The quality control system is approved by the engineer.

The contractor must have qualified personnel on the job or otherwise available.

The amount of cement to be used is determined by the contractor.

Acceptance testing is done by the state.

> The lot size is 6,000 yd.^2 Four tests are made per lot, stratified on the basis of 1 per sublot of 1,500 yd.^2 One air content test is made for each sublot.

Lower quality index, Q_L, is used as the basis for partial payments.

$$Q_L = \frac{\overline{X} - L}{R},$$

where

- L = lower specification limit,
- $\overline{X}$ = average of lot, and
- R = range of lot.

Acceptance is based on compressive strengths of cores taken from each sublot at random location at 14-26 days of age. Concrete can be rejected if honeycombing or segregation is noted.

WEST VIRGINIA

Quality control is the responsibility of the contractor. He must have a laboratory and a certified portland cement technician. He must submit a quality control plan for approval prior to start of job.

His quality control plan must show a frequency of tests in compliance with the state's minimum. The contractor's records must show the following:

Nature and number of observations made

Number and type of deficiencies found

Quantities approved and rejected

Nature of corrective action

All test results must be available to the state on a computer-acceptable medium.

Control charts must be maintained for aggregate gradations. Such charts become the property of the state.

The minimum frequency of tests established by the state are:

Fine aggregate:
- Gradation — daily
- Deleterious materials — daily
- Moisture — daily

Coarse aggregate:
- Gradation — daily
- P-200 — daily
- Moisture — as specified

Combined aggregate + cement:
- $\overline{A}$ — as specified

Plastic concrete:
- Air content (pavements) — one per 1/2-day production
- Air content (bridge superstructure) — one per batch
- Consistency (pavements) — one per 1/2-day production
- Consistency (bridge superstructure) — each fifth batch

Temperature — as specified

Yield — as specified

Strength — 1 set (3 cylinders) for 0-100 $yd.^3$

1 set each additional 100 $yd.^3$

The contractor has the option of using the predicted strength at 28 days based on curves established for the mix design (maturity concept).

Pavements are cored for acceptance. The cores are taken when the pavement is at least 28 days old, but not more than 91 days old. The results of the core tests are analyzed statistically.

For complete acceptance, the average of results must be equal to or greater than the 28-day design strength plus 1 standard deviation. Also, the average of any 5 consecutive tests must exceed the design strength.

Structural concrete is accepted when at least 93% of the cylinder test results are above the design strength (specification minimum). Also, 99.9% must be at least 1 σ above design stress.

The cement factor can be reduced up to 1/2-bag per cu. yd., if strength average is maintained at the levels indicated below.

$\overline{X} = f'_c$ (design strength) + $K_1 \sigma$ and $f'_c + K_2 \sigma$.

K_1 and K_2 are based on numbers of tests available.

When $n = 30$: $K_1 = 1.5$; $K_2 = 3.0$

When $n = 10$: $K_1 = 1.6$; $K_2 = 3.615$

K_1 and K_2 values are given for $n = 10$ through 30.

When n equals or exceeds 30, values for $n = 30$ apply.

APPENDIX B

SECTION 219 — HYDRAULIC CEMENT CONCRETE

Virginia Department of Highways & Transportation

"Road and Bridge Specifications"
January 1, 1978

1011

SECTION 219—HYDRAULIC CEMENT CONCRETE

Sec. 219.01 Description—Cement concrete shall consist of an approved hydraulic cement, a fine aggregate, a coarse aggregate, water, and such admixtures as may be specified, mixed in the approved proportions for the various classes of concrete, and by one of the methods hereinafter designated.

Sec. 219.02 Materials—The Contractor shall assume the responsibility for the quality control and condition of all materials during the handling, blending, and mixing operations. The Contractor shall assume responsibility for the initial determination and all necessary subsequent adjustments in proportioning of materials used to produce the specified concrete. The proportion of fine and coarse aggregate shall satisfy the necessary placing, consolidation, and finishing requirements, and the actual batch quantities shall be adjusted during the course of the work to compensate for changes in workability caused by differences in characteristics of aggregates and cements within the specification requirements. Such adjustments are to be made only by the Contractor and in such a way as not to change the yield.

(a) Cement shall conform to Section 216 and shall be Type II, unless otherwise permitted herein or otherwise specified in the contract. Type I-P cement may be used except in concrete pavement or bridge decks. Type III cement may be used in prestressed members, except piling. Type III Modified cement may be used in all prestressed members and when the use of High Early Strength Concrete is authorized.

(b) Fine aggregate shall conform to Section 202 for Grading A.

(c) Coarse aggregate shall be stone, air-cooled blast furnace slag, or gravel conforming to Section 203 for the class of concrete being produced.

(d) Water shall conform to Section 218.

(e) Admixtures shall conform to Section 217.

(f) White portland cement concrete shall conform with this section except as follows:

1. Cement shall be white portland cement conforming to the requirements of Section 216 for Type I portland cement, except that it shall contain not more than 0.55 percent by weight of ferric oxide (Fe_2O_3).
2. Fine aggregate shall consist of clean, hard, durable, uncoated particles of quartz composed of not less than 95 percent silica, free from lumps of clay, soft or flaky material, loam, organic or other injurious material and otherwise meeting the requirements of Section 202 for the class of concrete being produced. It shall contain not more than 3 percent inorganic silt by actual dry weight, when tested in accordance with AASHTO T11. Stone sands which have demonstrated that they produce an acceptable white concrete may also be utilized.
3. Coarse aggregate shall be crushed stone, or crushed or uncrushed gravel conforming to the requirements of Section 203 for the class of concrete being produced.

Sec. 219.03 Handling and Storing Materials—

(a) **Aggregate:** The Contractor shall furnish coarse aggregate conforming to Section 203.

Stockpiles of both coarse and fine aggregates may be placed adjacent to the batcher on ground that is denuded of vegetation, hard, and well drained. The different sizes and kind of aggregates shall be kept separate during transportation, handling, storage, and until batched. If necessary, partitions of suitable height and strength shall be constructed between the various stockpiles to prevent the different materials from becoming mixed. Care shall be taken to prevent segregation of the coarse and fine particles of aggregates from taking place during handling or hauling. The inclusion of foreign materials, when the aggregates are being removed from the transporting vehicles or storage piles and placed into the bin of the batcher or the skip of the mixer, will not be permitted.

Aggregates placed directly on the ground shall not be removed from the stockpiles within one foot of the ground until the final cleaning up of the work, and then only the clean aggregate will be permitted to be used.

The coarse aggregate shall be maintained to at least a saturated surface-dry moisture condition. The Contractor will be required to wet the stockpile the night previous to its use, and to sprinkle the aggregate during the day, as is deemed necessary by the Engineer.

If, in the opinion of the Engineer, the method of sprinkling used is not providing satisfactory results, he may require that an approved mechanical sprinkling system be provided.

Fine aggregate which has been washed shall not be used within 24 hours after being placed in the stockpile, or until surplus water has disappeared and the material has a uniform free moisture content. Stockpiles shall be so located and constructed that the surplus water will drain away from the stockpiles and the batcher.

Batching direct from the washing plant will not be permitted.

(b) **Cement:** Reclaimed cement or cement that shows evidence of hydration, such as lumps or cakes, shall not be used.

Loose cement shall be transported to the mixer either in tight compartments for each batch, or between the fine and coarse aggregate. Cement in original shipping packages may be transported on top of the aggregates, each batch containing the number of bags required.

All cement shall be stored in suitable weather-proof structures which will protect the cement from dampness. Small quantities may be stored in the open with approved waterproof protection.

(c) **Miscellaneous Materials:** Admixtures shall be stored and handled in such a manner that contamination or deterioration will be prevented. Liquid admixtures shall not be used unless thoroughly agitated. The use of admixtures that are partially frozen will not be allowed. When the amount of admixture required to give the specified results deviates appreciably from the manufacturer's recommended dosage, the use of this material shall be discontinued unless conditions justify a change in the dosage.

Sec. 219.04 Measurement of Materials—All measuring devices shall be subject to approval. Aggregates and cement shall be measured by weight. The fine and coarse aggregate and cement shall be weighed separately. Cement in standard packages, 94 pounds net per bag, need not be weighed, but bulk cement and fractional packages shall be weighed within an accuracy of one percent.

The mixing water shall be measured by volume or weight. When measured by volume, the holding tank shall be of sufficient size to hold the required quantity for any one batch. The water measuring device shall be readily adjustable and shall be capable of delivering the required amount. Under all operating conditions the device shall have an accuracy within one percent of the quantity of water required for the batch.

All aggregates shall be measured by weight within an accuracy of 2 percent. Prior to mixing concrete, the moisture content of the aggregates shall be determined and proper allowance made for the water content. Moisture determinations shall be performed prior to starting of mixing and subsequently thereafter as changes occur in the condition of the aggregate. The Contractor shall be responsible for performing moisture determinations as well as tests for slump and air content and providing the necessary testing equipment.

The amount of admixture required shall be added within a limit of accuracy of 3 percent and shall be dispensed by means of an approved, graduated, transparent, measuring device to the mixing water before it is introduced into the mixer. In the event more than one admixture is to be used, such admixtures shall be released into the mixing water in sequence rather than at the same instant. Once established, the sequence of dispensing admixtures shall not be altered unless specifically authorized by the Engineer. Admixtures shall be used in accordance with the manufacturer's recommendations.

All tolerances stated for measurement of materials will be applied to approved mix design quantities.

Sec. 219.05 Equipment Requirements—Equipment and tools necessary for handling materials and performing all parts of the work must meet with the approval of the Engineer.

(a) **Batching Equipment:** Bins with separate compartments for fine aggregate and for each required size of coarse aggregate shall be provided in the batching plant. Bins for bulk cement shall be so arranged that the cement is weighed on a scale separate from those used for other materials, and in a hopper entirely free and independent of the hoppers used for weighing the aggregates. The weighing hopper shall be properly sealed and vented to preclude dusting during operation. Each compartment shall be designed to discharge efficiently and freely into the weighing hopper. Means of control shall be provided so that the material may be added slowly and shut off with precision. A port or other opening shall be provided to remove any overrun of any one of the several materials from the weighing hopper. Weighing hoppers shall be constructed so as to prevent accumulation of materials and to discharge fully.

The scales for weighing aggregates and cement shall be of either the beam-type or the dial-type and shall be approved and sealed in accordance with Section 109.01. All beam-type scales shall be equipped with appropriate balancing means. A minimum of 10 fifty-pound test weights shall be made available at each plant for the purpose of verifying the continued accuracy of the weighing equipment. These test weights shall be calibrated by the Weights and Measures Regulatory Section of Virginia Department of Agriculture and Commerce at least once every two (2) years. A certificate of this calibration shall be forwarded to the Engineer in whose area the plant is located.

(b) **Safety Requirements:** Adequate and safe stairways to the mixer platform and sampling points shall be furnished and guarded ladders to other plant units shall be placed at all points where accessibility to plan operations is required.

All exposed fulcrums, clevises, and similar working parts of scales shall be kept clean. When beam-type scales are used, provision shall be made for indicating to the operator that the required load in the weighing hopper is being approached; the indicator shall indicate at least the last 200 pounds of load. All weighing and indicating devices shall be in full view of the operator while charging the hopper and he shall have convenient access to all controls.

(c) **Trucking Equipment:** All trucks, truck bodies, bulkheads, cement compartments and other equipment or accessories used in the proportioning and transportation of concrete materials, shall be so designed and operated as to insure the charging of the mixer, batch-by-batch, with the proper amount of each material, without over-spilling, intermixing of batches or wastage. Any units which, as determined by the Engineer, do not operate satisfactorily shall be removed from the project until corrected.

(d) **Mixers and Agitators:**

1. Mixers may be stationary mixers or truck mixers. Agitators may be truck mixers or truck agitators. Each mixer and agitator shall have attached thereto, in a prominent place by the manufacturer, a metal plate or plates on which is plainly marked the various uses for which the equipment is designed, the capacity of the drum or container in terms of the volume of mixed concrete and the speed of rotation of the mixing drum or blades. Each stationary mixer shall be equipped with an approved timing device that will not permit the batch to be discharged until the specified mixing time has elapsed. Each truck mixer shall be equipped with an approved counter by which the number of revolutions of the drum or blades may be readily verified.
2. The mixer shall be capable of combining the ingredients of the concrete into a thoroughly mixed and uniform mass and of discharging the concrete with a satisfactory degree of uniformity as indicated in Paragraph 4 herein.
3. The agitator shall be capable of maintaining the mixed concrete in a thoroughly mixed and uniform mass and of discharging the concrete with a satisfactory degree of uniformity as indicated in Paragraph 4 herein.
4. All mechanical details of the mixer or agitator, such as water measuring and discharge apparatus, condition of the blades, speed of rotation of the drum, general mechanical condition of the unit and cleanliness of the drum, shall be checked before use of the unit is permitted. The Engineer may require, from time to time, consistency tests of individual samples at approximately the beginning, midpoint, and end of the load. If the consistency measurements vary by more than 2 inches for slump between the high and low values, the mixer or agitator shall not be used unless the condition is corrected.

Sec. 219.06 Worker Qualification—All sources supplying concrete to the Department shall be required to have present during the batching operations, a Certified Concrete Batcher and/or a Certified Concrete Technician. A Certified Concrete Batcher is that person who actually performs the batching operation. He shall never initiate adjustments and will be permitted to implement adjustments only at the direction of a

Certified Concrete Technician, unless his certification carries this special authorization. A Certified Concrete Technician is that person who is capable of performing adjustments in the proportioning of materials used to produce the specified concrete, should such adjustments prove necessary. Certification shall be by the Department, awarded upon satisfactory completion of an examination.

The concrete producer shall so plan his batching operations that delays do not occur due to the absence of certified personnel. In cases of emergency, the concrete producer shall have readily available for service a Certified Concrete Batcher and/or a Certified Concrete Technician to replace the regular personnel assigned to these jobs. Should cases of extreme emergency arise during actual batching operations, this requirement will be temporarily waived by the Engineer in order to complete the placing of concrete on the portion or section of a structure involved. Additional batching operations shall not be initiated until the services of a Certified Concrete Batcher and/or a Certified Concrete Technician have been obtained.

The Department's inspector will never assume by act or word the responsibility of batch control adjustments, calculations, or the setting of dials, gages, scales and meters.

Sec. 219.07 Classification and Proportioning of Concrete Mixtures—The concrete shall be proportioned to secure the strength and durability required for the pavement or the part of the structure in which it is to be used.

The Contractor shall submit for approval concrete mix design(s) meeting the requirements in Table II-15 for the specified class of concrete prior to mixing any concrete

The Contractor shall furnish and incorporate an approved "Water-Reducing and Retarding Admixture" in Class A4 bridge deck concrete, unless waived in writing by the Engineer, and in other concrete when conditions are such that initial set may occur prior to completion of approved finishing operations. An approved "Water-Reducing Admixture" shall be furnished and incorporated in concrete when necessary to provide the required slump without exceeding the maximum water-cement ratio and shall be used in Class A4 bridge deck concrete when the requirement for a "Water-Reducing and Retarding Admixture" is waived by the Engineer. The two admixtures shall not be used together in the same concrete batch. All costs for admixture(s) shall be included in the price bid for the respective concrete item.

Concrete shall be air-entrained unless otherwise specified. The air content shall be as required in Table II-15. Air content will be determined by the pressure method, AASHTO T152, for concretes with natural aggregates, and by the volumetric method, AASHTO T196, for concretes with aggregates of high absorptions, such as slags or expanded shales, clays or slates.

The classes and uses of concrete recognized in these specifications are shown in Table II-15.

The quantities of fine and coarse aggregates necessary to conform to these specifications in regard to consistency and workability shall be determined by the method described in "Recommended Practice for Selecting Proportions for Concrete" (ACI 211), except that proportions shall be computed on the absolute volume basis and the 10 percent adjustment allowed in Table 5.2.6 will not be permitted; or "Recommended Practices for Selecting Proportions for Structural Lightweight Concrete" (ACI 211.2). The actual quantities used, as determined by the methods described herein, shall not deviate more than plus or minus 5 percent from such quantities.

TABLE II-15
REQUIREMENTS FOR PORTLAND CEMENT CONCRETE

CLASS OF CONCRETE	Design Minimum Laboratory Compressive Strength at 28 Days psi	Aggregate Size number	Nominal Maximum Aggregate Size	Minimum Grade Aggregate	Cement Content lbs./cu. yd. minimum	Maximum Water lbs. Water Per lbs. Cement	Consistency, Inches Slump	Consistency, Inches Ball Penetration	Air Content percent
A5 Prestressed and other special designs	5000	57	1 in.	A	635	0.49	0-4	0-2	4 ± 2
A4 Posts and rails*	4000	7	½ in.	A	635	0.47	2-5	1-3	7 ± 2
A4 General Use	4000	57	1 in.	A	635	0.47	2-4	0-2	6½ ± 1½
A3 General Use	3000	57	1 in.	A	588	0.49	1-5	0-3	6 ± 2
A3 Paving	3000	57	1 in.	A	564	0.49	0-3	0-2	6 ± 2
B2 Massive or lightly reinforced	2200	57	1 in.	B	494	0.58	0-4	0-2	4 ± 2
C1 Massive unreinforced	1500	57	1 in.	B	423	0.71	0-3	0-2	4 ± 2
T3 Tremie Seal	3000	57	1 in.	A	635	0.49	3-6		4 ± 2

A set retarder admixture shall be used unless waived in writing by the Engineer.

*Aggregate size No. 7 shall be used in concrete posts, rails (not parapet walls) and other thin sections above top of bridge deck slabs when necessary for ease in placement

Note: The Contractor, at his option, may substitute a higher class of concrete for that specified at no additional cost to the Department.

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In the event concrete can not be obtained with the required workability or consistency or within the maximum water content with the materials furnished by the Contractor, he shall make such changes as are necessary to secure the desired properties subject to the limiting requirements in Table II-15 and the approval of the Engineer. When the void content of the fine aggregate is more than 50.5 percent and the concrete does not have the desired properties, the Contractor shall change to a fine aggregate having a void content of less than 50.5 percent. In lieu of changing the fine aggregate, the Contractor may take one or more of the following actions: (1) use an approved water reducing admixture; (2) increase the cement content; (3) change the source of coarse aggregate; (4) in hot weather, add ice or otherwise reduce the temperature to increase the workability; (5) other recommendation by the Contractor as approved by the Engineer. However, when any of the options are exercised, the Contractor shall make a trial batch to verify that the concrete of the required workability and consistency is within the maximum water content. When the fineness modulus of the fine aggregate changes more than 0.2 from the original design and the concrete does not have the desired properties, the concrete mix shall be re-designed. The Contractor will not be compensated for any additional costs which may accrue as a result of such adjustment.

Sec. 219.08 **Mixing**—The method of mixing shall be approved by the Engineer prior to the beginning of any concrete work.

The volume of concrete mixed per batch shall not be less than 15 percent nor more than 110 percent of the mixer's rated capacity.

Concrete which becomes nonplastic, unworkable, or outside the limits of the slump specified shall not be used. The use of retempered concrete will not be permitted. Delivery of concrete shall be so regulated that placing is at a continuous rate. The intervals between delivery of batches shall not be so great as to allow the concrete in place to harden partially.

Mixing shall conform to one of the following methods:

(a) **Mixing at Job Site:** Concrete shall be mixed in a batch mixer so designed as to positively insure a uniform distribution of the materials throughout the mass. When bag cement is used, batches shall be proportioned on the basis of integral bags of cement.

Mixing shall be in accordance with paragraph (b) 3.

Upon the cessation of mixing for more than 30 minutes, the mixer shall be thoroughly cleaned.

(b) **Ready-Mixed:** Ready-mixed concrete shall be mixed concrete delivered to the designated point ready for use. The ready-mix plant shall be approved prior to use, and in the event satisfactory quality concrete is not produced, such approval will be withdrawn.

Each load of transit or shrink mixed concrete shall be accompanied by a form issued by the plant Inspector showing the time the cement was introduced to the mix and the amount of mixing that has been performed. The form shall be delivered to the Inspector at the site of the work. Loads which do not carry such information, except as stated hereinafter, or which do not arrive in satisfactory condition shall not be used in the work.

In lieu of inspecting the batching of every load of concrete at the plant and testing at the point of delivery, small quantities of concrete for miscellaneous items may be accepted by the Engineer based upon batch information furnished by the Contractor (or Supplier) on weight tickets; and, based upon visual examination or testing at the point of delivery. The frequency of batch verification by an Inspector at the source and testing for acceptance at the point of delivery will be established by the Engineer based upon the Department's current acceptance program and local conditions encountered.

Upon the cessation of mixing for more than 30 minutes, the mixer shall be thoroughly cleaned. The use of wash water as a portion of total mix water for subsequent batches will not be permitted.

Each batch of concrete shall be delivered to the site of the work and discharged within the time specified herein.

The allotted time will begin the instant the cement is introduced to the mix.

Maximum Time Between Introduction of Cement to the Mix and Discharge, Hours

	Air Temperature		
	Up to 80°F	**80-90°F**	**Above 90°F**
Agitator Type Haul Equipment Class A3—General Use (Retarded)	2½	2	1½
Other Classes and Usages (Retarded and Unretarded)	1½	1¼	1
Nonagitator Type Haul Equipment—All Concrete	1	¾	½

The times given herein for retarded concrete are provided to accommodate the physical limitations of a formed section or scattered locations of small increment placements and shall not be used to accommodate slow and noncontinuous placements caused by poor planning or scheduling, inadequate equipment or personnel, or excessive haul distances.

Mixing and delivery shall be in accordance with one of the following:

1. **Transit Mixing**—The concrete shall be mixed in a truck mixer. Mixing shall begin immediately after all ingredients are in the mixer and shall continue for not less than 70 nor more than 125 revolutions of the drum or blades at not less than 14 nor more than 20 revolutions per minute unless otherwise directed by the Engineer.

   Additional rotations of the drum or blades shall be at the rated agitating speed. The mixer shall be operated within the capacity and speed of rotation designed by the manufacturer of the equipment.

2. **Shrink Mixing**—All materials, including water, shall be partially mixed in a stationary mixer for at least 30 seconds and the mixing completed in a truck mixer with not less than 60 revolutions nor more than 100 revolutions of the drum or blades at the rated mixing speed, unless a lesser or greater number of revolutions is directed by the Engineer. Additional rotations of the drum or blades shall be at agitating speed. The stationary and truck mixers shall be operated within the capacity and speed of rotation designed by the manufacturer of the equipment.

3. **Central Mixing**—The concrete shall be completely mixed in a stationary mixer and the concrete transported to the point

of delivery in agitator or nonagitator type equipment. The use of nonagitator type equipment will be approved only when the location of the plant is in the immediate vicinity of the project.

The mixing time for mixers having a capacity of one cubic yard or less shall be a minimum of 60 seconds. Mixing time for mixers having a capacity of more than one cubic yard and less than 10 cubic yards shall be a minimum of 75 seconds. unless a lesser time is approved by the Engineer following an evaluation of performance tests. Performance tests shall be conducted by a recognized commercial laboratory at the expense of the Contractor in accordance with VTM-17. The lesser times will be approved providing the requirements of VTM-17 are met.

The requirements stated in VTM-17 shall not be construed as a nullification of the requirements of Table II-15. In the event subsequent evaluation check tests performed by the Department indicate that the reduced mixing time is not satisfactory, the Department reserves the right to require the Contractor to reestablish the necessary mixing time.

In no case shall the mixing time be reduced below 40 seconds. The mixing time is defined as starting when all the solid materials are in the mixing compartment and ends when any part of the concrete begins to discharge. The mixer shall be operated at the drum speed shown on the name plate of the approved mixer. Any concrete mixed less than the specified time will be rejected.

Mixing time for mixers having a capacity of over 10 cubic yards shall be as determined by the Engineer.

Bodies of nonagitating equipment used for transportation of concrete shall be smooth, mortar-tight metal containers and shall be capable of discharging the concrete at a satisfactory controlled rate without segregation. Upon discharge of the concrete, the body of the equipment shall be free of all concrete. Concrete shall be delivered to the site of the work in a thoroughly mixed and uniform mass. The Engineer may require from time to time, consistency tests of individual samples at approximately the beginning, midpoint and end of the load. If these consistency measurements vary by more than 2 inches for slump between the high and low values, mixer or agitator equipment shall be used in lieu of nonagitating equipment, unless the condition is corrected.

(c) **Hand Mixing:** Hand mixing will not be permitted except in case of emergency and with special permission. When permitted, the batches shall not exceed ½ cubic yard and shall be mixed on watertight, level platforms in a manner approved by the Engineer.

Sec. 219.09 **Mixing Limitations**—The Contractor shall be responsible for the quality of the concrete placed in any weather or atmospheric conditions.

At the time of placing, concrete shall have a temperature in accordance with the following:

(a) Class A3 general use concrete used in the construction of incidental items specified in Division V, except retaining walls, shall be not less than 40°F nor more than 95°F.

(b) Class A3 paving concrete placed by the slip-form method and containing an approved water reducer shall be not less than 40°F nor more than 95°F.

(c) Class A4 concrete used in the construction of bridge decks shall be not less than 40°F nor more than 85°F.

(d) Retaining walls and other concrete not specified in (a), (b) or (c) herein shall be not less than 40°F nor more than 90°F.

In cold weather, the water and aggregates may be heated to not more than 150°F to maintain the concrete at the required temperature. The heating apparatus shall be such that the materials will be heated uniformly and preclude the possibility of the occurrence of overheated areas which might injure the materials. Live steam shall not come in contact with the aggregates. Cement shall not be heated. Heating equipment or methods which alter or prevent the entrainment of the required amount of air in the concrete shall not be used. Materials containing frost, lumps, crusts or hardened material shall not be used.

In hot weather, the aggregates and/or the mixing water shall be cooled as necessary to maintain the concrete temperature within the specified maximum.

Sec. 219.10 Quality Control — The Contractor shall be responsible for the quality control of the concrete, including the type and frequency of sampling and testing deemed necessary to ensure that the concrete he produces complies with the specifications.

A Department representative shall be provided free access to plant production records, and, if requested, informational copies of mix design, materials certificates, and sampling and testing reports.

Sec. 219.11 Acceptance of Production — The Department will be responsible for acceptance of production. The following acceptance procedures will be used to determine overall the acceptability of each lot of concrete production. A lot is defined as a definite quantity of concrete manufactured under conditions of production that are considered to be uniform. Unless otherwise stated, for structural and incidental concrete all the concrete of a given class included as a separate bid item in a contract will be considered a single lot. For paving concrete the total pavement shall be considered a single lot, except where the volume exceeds 1,000 $yd.^3$. For such large projects the nominal lot size will be 1,000 $yd.^3$. In addition to these procedures, the Department may reject any concrete which is obviously defective, or test and reject any concrete that does not meet the requirements of these specifications.

Concrete which ultimately fails compressive strength tests and, based on an analysis by the Department, is so located as to cause an intolerably detrimental effect on a structure or pavement, will be ordered removed at the Contractor's expense and replaced with acceptable concrete. Replacement concrete shall be produced and will be accepted in accordance with these specifications (Section 219).

(a) Temperature: The Department's representative may determine the temperature of any batch of concrete after delivery to the job. All batches with temperatures not in compliance with Section 219.09 will be rejected and removed from the job.

(b) Water-Cement Ratio: Any batch of concrete that exceeds the water-cement ratio specified in Table II-15 will be rejected and removed from the job. Additionally, batches with less than the minimum cement content specified in Table II-15 will be rejected and removed from the job.

(c) Tests for Air Content, Consistency, and Strength: Sampling and testing for air content, consistency, and strength shall be conducted in accordance with Section 219.12.

Sec. 219.12 Sampling and Testing —

(a) Initial and Monitoring Sampling and Testing: The first batch during each production day shall be sampled and tested for temperature, air content, and slump prior to further discharge. In the event of noncompliance, the material shall be rejected and each succeeding batch shall be similarly sampled and tested until production is demonstrated to be in compliance with the specifications. Subsequent to the initial sampling and testing, air content and slump will be monitored by the Department as needed to ensure that the specification requirements are consistently being met for each class of concrete prior to discharge into the forms.

Sampling for temperature, air content, and slump may be in accordance with AASHTO T-141, which permits a sample to be taken after 2 ft.^{3} have been discharged. Initial and monitoring air content tests may be performed by AASHTO T-199. Should any determination yield a result which is outside the allowable range of air content or consistency, the following action will be taken.

(1) The inspector will immediately perform a recheck determination and should the results confirm the original test, the load will be rejected. The air content determination for this recheck must be made using AASHTO T-152 (air pressure meter) or T-196 (volumetric method).

(2) The Contractor's representative will be informed of test results immediately.

(3) The Contractor's representative shall be responsible for notifying the producer of test results through a preestablished means of communication. If the recheck test shows compliance with the specification, the concrete may be placed in the structure.

Any batch of concrete having a consistency or, after recheck, an air content that deviates from the requirement specified in Table II-15 will be rejected and shall be removed from the job.

(b) Acceptance Samples for Air Content and Compressive Strength: Samples for final acceptance based on air content and compressive strength will be selected by a statistically valid random procedure as designated by the Department's representative. The portion secured for each test is to be taken after not less than 2 ft.^{3} has been discharged into a suitable container other than forms. The frequency of sampling will vary according to lot size and the type of structure in which the concrete is used. Minimum frequencies are as given in 219.12(c).

(c) Frequency of Acceptance Sampling:

(1) Bridge decks (total deck — one lot)

- Lot sizes up to 150 yd.^{3} — Select one sample randomly from each of 3 equal increments (sublots).

- Lot sizes greater than 150 yd.^{3} — Establish the number of equal size sublots of approximately 50 yd.^{3} ($<$ 55 yd.^{3}). Select one sample randomly from each sublot.

(2) Structural concrete (bridge members [except decks], box culverts, retaining walls, and miscellaneous). A lot is defined as all material of the same class in a separate bid item of a contract.

- Lot sizes up to 150 yd.^{3} — Select one sample randomly from total lot. For miscellaneous concrete of lot sizes less than 50 yd.^{3} sampling and testing may be waived and concrete accepted by visual inspection, when quality is deemed not critical to performance.

- Lot sizes 150 yd.^{3} to 300 yd.^{3} — Select one sample randomly from each of 3 sublots.

- Lot sizes greater than 300 yd.^{3} — Establish the number of equal size sublots of approximately 100 yd.^{3} ($<$ 110 yd.^{3}). Select one sample randomly from each sublot.

(3) Paving concrete:

(a) For projects less than 1,000 yd.^{3} — Define lot as all material of the same class in a separate bid item of the contract. Establish the number of equal size sublots of approximately 100 yd.^{3} ($<$ 110 yd.^{3}). Select one sample randomly from each sublot.

(b) For projects greater than 1,000 yd.^{3} — Divide the total volume of concrete into approximately equal lots of 1,000 yd.^{3}. Establish and test sublots as defined in (a) above.

(d) Initial Acceptance Procedure for Air Content and Slump of Bridge Deck Concrete: At the start of a concrete production lot for a bridge deck, every batch shall be sampled and tested (100% sampling and testing) for air content and slump as described in 219.12a. Random sampling and testing for air content or slump or both at the rate of one for every five successive batches may be substituted for 100% sampling and testing when the test results for three successive batches are within the specification limitations for air content and slump. However, 100% sampling and testing will be reinstated for that particular property when a test result for any sample is outside the specification limit.

(e) Final Acceptance Procedure: Final acceptance and the pay factor for all concrete shall be in accordance with Section 219.13.

Sec. 219.13 Quality Level Determination and Pay Factors

(a) Air Content: In addition to the initial and monitoring tests, tests for air content shall be made on each acceptance sample using AASHTO Method T-152 (air pressure method) or T-196 (volumetric method). The results of these tests will be statistically analyzed using the procedures given in VTM-XXX to determine the limiting quality levels for entrained air in the concrete in place, which will be used in determining the final pay factors for each lot of concrete. Results on samples taken for initial or monitoring purposes will not be included in this analysis, unless they are also selected by the random selection procedure as acceptance samples.

No reduction in payment will be made for results outside the specification limits for air content, when the statistical analysis indicates that with a producer's risk of 5%, 90% or more of all production in a lot meets the specification. If the analysis indicates that there is a 95% probability that less than 90% of the production is within the specified limits, then a reduced pay factor will be applied to the concrete portion of the bid item that constitutes the lot. Such reduced pay factor will be computed by the Department as follows:

$$RP_A = (QL_A + 10)/100,$$

where

RP_A = reduced pay factor with respect to air content (figure will not be less than 0.70), and

QL_A = adjusted quality level (percent within specification limits) with respect to air content (based on a statistical analysis of all valid test data for a producer's risk of 5% as described in VTM-XXX).

(b) Compressive Strength: The final acceptance of all concrete will be on the basis of 28-day test results determined on sets of three 4 in. x 8 in. cylinders made from each acceptance sample. Except under the special conditions described in VTM-XXX, the average result from all cylinders in a set is considered a single valid test result. No reduction for noncompliance with the specified limits for strength will be made, if the statistical analysis of all valid 28-day strength data made in accordance with VTM-XXX indicates that with a producer's risk of 5%, 90% or more of all production of a given mix equals or exceeds the strength requirement. If less than 90% of the production meets the requirement, a reduced pay factor will be applied to the concrete portion of all items containing the involved concrete. The reduced pay factor will be computed by the Department as follows:

$$RP_S = (QL_S + 10)^2/10,000,$$

where

RP_S = reduced pay factor with respect to 28-day compressive strength (figure will not be less than 0.70), and

QL_S = adjusted quality level (percent within specification limits) with respect to 28-day compressive strength (based on a statistical analysis of all valid test data corrected for a producer's risk of 5% as described in VTM-XXX).

(c) Combined Pay Factor for Acceptance: In the event that the computed limiting qualities for both air content and 28-day strength are below the required levels, a net reduced pay factor will be computed as follows:

$$RP_N = RP_A \times RP_S$$

This figure will not be less than 0.50.

RP_N will be projected periodically during the course of production. In the event that RP_N is less than 1.00, payments will be reduced accordingly.

If any time during production either RP_A or RP_S is projected to be at a level of 0.70 or less and the Contractor is taking no effective action to improve the deficient quality levels, the Department's representative will order production ceased until the deficiencies are effectively corrected.

Sec. 219.14 Basis of Payment — If the concrete is subject to a price reduction, the following procedures will apply.

(a) For concrete bid by the unit (yd.^{3}, etc.)

$$PR = Q \times BP \times (1-RP_N),$$

where

PR = price reduction in dollars,

Q = quantity of concrete in the involved lot expressed in the same units as the bid price,

BP = bid price per unit, and

RP_N = net reduced pay factor.

(b) For concrete included in a lump sum

$$PR = Q/T \times LS \times (1-RP_N),$$

where

T = total quantity of concrete in the item,

LS = lump sum bid price, and

other symbols are the same as in (a).

(c) Reduction in pay factor for low compressive strengths in small lots: When the average 28-day strength result for concrete represented by less than 3 acceptance samples is below the specified f'_c, the Department may require the removal and replacement of the lot if the deficiency is judged to be critical to the performance of the structure or the batch represented by each low test result may be accepted in accordance with Table II-16, unless the contractor elects to replace the affected concrete.

TABLE II-16

Pay Factor Schedule for Compressive Strength at 28-Days
(Lots represented by less than three samples)

Average Sample Test Result from Batch	Pay Factor
Not less than 0.98 f'_c	1.00
Not less than 0.96 f'_c	.95
Not less than 0.94 f'_c	.85
Less than 0.94 f'_c	.70

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Sec. 219.15 **High-Early-Strength Portland Cement Concrete**—When high-early-strength portland cement concrete is authorized, it shall conform to all the requirements of Table II-15, except that the 28-day strength shall be obtained in 7 days. Up to 800 pounds per cubic yard of cement may be used to produce high-early-strength concrete in lieu of using Type III Modified cement. Monitoring, acceptance procedures, and pay factors shall apply as described in Sections 219.11, 219.12, 219.13 and 219.14.

Sec. 219.16 Pretensioned Prestressed Concrete Class A5

Same as present 219.14.

APPENDIX C

DETERMINATION OF THE ADJUSTED QUALITY LEVEL OF CONCRETE PRODUCTION BASED ON A 5 PERCENT PRODUCER'S RISK (VTM-XXX)

1. Scope

1.1 This method describes the specific steps and computations required to determine the adjusted statistical quality level indicated by a series of test data after correction is applied to assure a producer's risk of no more than 5 percent. The test data are assumed to represent a single statistical population with a normal distribution.

2. Definitions and Symbols

2.1 Average, $\overline{X}$ — the numerical average of all test results. A test result may involve one or more determinations made at the same time or on test specimens made from the same portion of material.

2.2 Estimate of Standard Deviation, s — the calculated standard deviation based on all valid test results measuring the same parameter, assuming the data have a normal distribution.

2.3 Quality Level — An estimate of the portion of a population within the specification limits.

2.4 Producer's Risk Correction (Cpr) — a correction applied to the average of test results so that there is at least 95% certainty that the adjusted quality level calculated on the basis of the corrected average is no higher than indicated.

2.5 Adjusted Quality Level — an estimated quality level for which there is a 95% certainty that the true quality level does not exceed. (Stated differently — there is only a 5% risk of rejecting a quantity of production equal to the minimum quality level defined as being acceptable without a reduction in the pay factor.)

3. Procedure

3.1 Determine the average, $\overline{X}$, and the estimated standard deviation, s, of all valid test results.

3.1.1. A valid test result for air content is a single determination made by the AASHTO T-152 or T-196, or the average of three determinations made by AASHTO T-199 (Chace air indicator) on the same batch of concrete.

3.1.2 For concrete strengths, the results of all tests on concrete cylinders made from the same batch and tested at the same age shall be averaged to constitute a single test result. If the range of results on two cylinders exceeds 10% of the average of the two, the test result is not valid. If the range of results (from lowest to highest) on three cylinders exceeds 15% of the average of the three, the average of three results is not a valid test result; however, should one of the three cylinders be obviously defective and the other two agree to within 10% of their average, the average of those two shall be considered a valid test result.

3.2 Determine the producer's risk correction (Cpr) to establish a 5% producer's risk; i.e., if reduced payment is applied, there is at least 95% certainty that it is warranted. The equation for Cpr is

$$Cpr = \frac{1.65\ s}{\sqrt{T}},$$

where

s is the standard deviation and

T is the estimated final total number of samples, n. T may be corrected periodically until the final number of tests (n) is known. (T = n).

3.3 Determine the corrected average, $\overline{X}_c$, for a 5% producer's risk as follows:

3.3.1 When a minimum specification limit is stated — add the Cpr determined in 3.2 to the average of the test results ($\overline{X}_c = \overline{X} + Cpr$).

3.3.2 When a maximum specification limit is stated, subtract the Cpr determined in 3.2 from the average of the test results.

3.3.3 When both minimum and maximum specification limits are stated, determine the corrected average as in 3.3.1 when the average of the tests are below the mid range of the specification. When the average of the tests are above the mid range of the specifications, determine the corrected average as in 3.3.2.

If the indicated correction is greater than that needed to place the corrected average at the midpoint of the specification range, use the midpoint as the corrected average.

3.4 Determine Quality Level.

3.4.1 Calculate the parameter z as follows:

3.4.1.1 Lower specification limit, or when $\overline{X}_c$ is below mid-point of specification range.

$$z = \frac{\overline{X}_c - LL}{s}$$

3.4.1.2 Upper specification limit, or when $\overline{X}_c$ is above mid-point of specification range.

$$z = \frac{UL - \overline{X}_c}{s},$$

where

$\overline{X}_c$ = corrected average from 3.3,

LL = lower specification limit, or low limit of a specified range, and

UL = upper specification limit or upper limit of a specified range.

3.4.2 Determine the indicated quality level from Table 1 as follows:

Read V from the table

Quality Level (QL) = (V x 100) + 50

Round to nearest 0.1.

Example:

If specification for air content is 6 ± 1.5, corrected average $\overline{X}_c$ = 5.7, and standard deviation is 0.80, then

$$z = \frac{5.7 - 4.5}{.8} = 1.50,$$

V from table = .4332, and

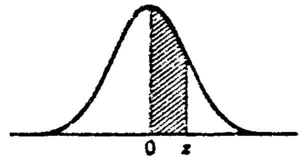
QL = (.4332 x 100) + 50 = 93.3.

If corrected average = 6.3,

$$z = \frac{7.5 - 6.3}{.8} = 1.50 \text{ and}$$

$$QL = (.4332 \times 100) + 50 = 93.3.$$

Table 1. Quality Level Table.



Second decimal place of Z

z	.00	.01	.02	.03	.04	.05	.06	.07	.08	.09
0.0	.0000	.0040	.0080	.0120	.0160	.0199	.0239	.0279	.0319	.0359
0.1	.0398	.0438	.0478	.0517	.0557	.0596	.0636	.0675	.0714	.0753
0.2	.0793	.0832	.0871	.0910	.0948	.0987	.1026	.1064	.1103	.1141
0.3	.1179	.1217	.1255	.1293	.1331	.1368	.1406	.1443	.1480	.1517
0.4	.1554	.1591	.1628	.1664	.1700	.1736	.1772	.1808	.1844	.1879
0.5	.1915	.1950	.1985	.2019	.2054	.2088	.2123	.2157	.2190	.2224
0.6	.2257	.2291	.2324	.2357	.2389	.2422	.2454	.2486	.2518	.2549
0.7	.2580	.2612	.2642	.2673	.2704	.2734	.2764	.2794	.2823	.2852
0.8	.2881	.2910	.2939	.2967	.2995	.3023	.3051	.3078	.3106	.3133
0.9	.3159	.3186	.3212	.3238	.3264	.3289	.3315	.3340	.3365	.3389
1.0	.3413	.3438	.3461	.3485	.3508	.3531	.3554	.3577	.3599	.3621
1.1	.3643	.3665	.3686	.3708	.3729	.3749	.3770	.3790	.3810	.3830
1.2	.3849	.3869	.3888	.3907	.3925	.3944	.3962	.3980	.3997	.4015
1.3	.4032	.4049	.4066	.4082	.4099	.4115	.4131	.4147	.4162	.4177
1.4	.4192	.4207	.4222	.4236	.4251	.4265	.4279	.4292	.4306	.4319
1.5	.4332	.4345	.4357	.4370	.4382	.4394	.4406	.4418	.4429	.4441
1.6	.4452	.4463	.4474	.4484	.4495	.4505	.4515	.4525	.4535	.4545
1.7	.4554	.4564	.4573	.4582	.4591	.4599	.4608	.4616	.4625	.4633
1.8	.4641	.4649	.4656	.4664	.4671	.4678	.4686	.4693	.4699	.4706
1.9	.4713	.4719	.4726	.4732	.4738	.4744	.4750	.4756	.4761	.4767
2.0	.4772	.4778	.4783	.4788	.4793	.4798	.4803	.4808	.4812	.4817
2.1	.4821	.4826	.4830	.4834	.4838	.4842	.4846	.4850	.4854	.4857
2.2	.4861	.4864	.4868	.4871	.4875	.4878	.4881	.4884	.4887	.4890
2.3	.4893	.4896	.4898	.4901	.4904	.4906	.4909	.4911	.4913	.4916
2.4	.4918	.4920	.4922	.4925	.4927	.4929	.4931	.4932	.4934	.4936
2.5	.4938	.4940	.4941	.4943	.4945	.4946	.4948	.4949	.4951	.4952
2.6	.4953	.4955	.4956	.4957	.4959	.4960	.4961	.4962	.4963	.4964
2.7	.4965	.4966	.4967	.4968	.4969	.4970	.4971	.4972	.4973	.4974
2.8	.4974	.4975	.4976	.4977	.4977	.4978	.4979	.4979	.4980	.4981
2.9	.4981	.4982	.4982	.4983	.4984	.4984	.4985	.4985	.4986	.4986
3.0	.49865	.4987	.4987	.4988	.4988	.4989	.4989	.4989	.4990	.4990
4.0	.4999683									