FINAL REPORT

IMPROVED 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 is the final report of a study of the application of statistical concepts to specifications for hydraulic cement concrete as used in highway facilities. It reviews the general problems associated with the application of statistical techniques to hydraulic cement concrete, and discusses the potential advantages and disadvantages to applying such techniques to concrete used in the construction of transportation facilities.

During the course of the research reported here, it was found that for the Virginia Department of Highways and Transportation, contracts for concrete structures generally involved small volumes of concrete, and that the usual frequency of sampling and testing did not provide sufficient test results for establishing specifications based on usually recommended risks to both the contractor and the state. Increases in the frequency of testing to provide the recommended risks would result in excessive increases in costs. Accordingly, procedures for acceptance of concrete on the basis of small-to-medium sample sizes at increased statistical risks, but based on sound engineering judgement, were developed and are included in the report.

Also included are complete recommendations for a revised specification for hydraulic cement concrete and a discussion of the statistical significance of the recommended changes. Recommended revisions to the Virginia Test Manual and the Instructions to concrete inspectors that would be needed should the revised specification be accepted are included in the appendices. Also included as an appendix is a resumé of practices and requirements in other states using statistical concepts in their specifications for hydraulic cement concrete.

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INTRODUCTION

In 1981, the Virginia Highway and Transportation Research Council, in cooperation with the Federal Highway Administration, initiated a program to improve its specifications for hydraulic cement concrete. The ultimate aim of the program is to establish performance related specifications for hydraulic cement concrete used in the construction and rehabilitation of ground transportation facilities. The tasks outlined in the initial study were: (1) to review the state of the art for using statistical concepts for hydraulic cement concrete; (2) to review present quality control and acceptance tests normally employed for hydraulic cement concrete and to make an assessment of their relation to performance; (3) to prepare an interim report summarizing the findings of tasks 1 and 2 and presenting recommendations concerning revisions of the Virginia Department of Highways and Transportation specifications for hydraulic cement concrete; and (4) to evaluate the proposed specifications by simulation during actual construction.

The interim report on the project was prepared and published in March 1982.(1) The findings presented in the interim report led to a modification of task 4 of the project. The primary effort of the modified work plan for task 4 was to establish the practicability of the proposed revisions to the specifications for hydraulic cement concrete, and to make final recommendations for changes needed. The identification of educational needs for implementing changes and revisions to instructional manuals, where needed, was also to be accomplished. Under the revised working plan, it was stipulated that studies to specifically relate the characteristics of the concrete to performance will be made under a different project or projects.

The findings of task 4 of this study show that significant changes are required in the initial recommendations contained in the interim report. Accordingly, to avoid confusion, this final report has been prepared to completely replace the interim report.

Pertinent information contained in the initial report is repeated here, and initially recommended changes and discussions thereof have been replaced with the final recommendations and justification for the changes.

PROBLEMS ASSOCIATED WITH QUALITY ASSURANCE FOR CONCRETE

Considerable knowledge has been developed concerning those attributes that characterize high quality hydraulic cement concretes, 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 relating to concrete.

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 exact relationship of the test data based on cylinders or other fabricated test specimens to the actual characteristics of the hardened concrete in the pavement structure. This uncertainty exists regardless of how much test data are available or how they may be analyzed. Consequently, even though there have been considerable efforts over the last 15 to 20 years to make use of statistical principles in quality assurance for all highway construction, some agencies are reluctant to base acceptance requirements for concrete 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. Other agencies support the use of statistical probabilities and 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 availability of specific documentation provides a basis for an equitable settlement of the dispute.

Significant improvements in the specifications for portland cement concrete for highway facilities can be achieved through a middle-of-the-road approach that utilizes statistical concepts to the extent possible, but also recognizes the engineering problems and the judgement factors. 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 a low risk of making a wrong decision. It is also important that a proper degree of flexibility be built into the system to permit the exercise of sound engineering judgement in all cases.

The specifications and quality assurance procedures now 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 to the extent possible, 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 principles can be applied with very little, if any, additional effort on the part of either the state or the contractor. The data would also serve as a basis 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 serve as guidelines for the recommended 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 specifications, can be determined.

2. The revised specification should be such that contractors and concrete producers with good quality control will have an 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 provides an incentive for the contractor to improve his quality control procedures and to minimize his risk of reduced payments.

4. The specifications 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.

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.(2) 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.(3) 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.

The recommended practice established by the American Concrete Institute (ACI 214) for judging the acceptability of concrete strength results includes four criteria, all of which are based on statistical concepts.(4) 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 in ACI 214 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 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 (Criterion No. 2) 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).

A third criterion given by ACI 214 is that there is a certain probability that a random individual test result will fall below f'_c by more than a certain amount. ACI 318 stipulates that the probability of a random test result being more than 500 lb./in.^{2} (3.45 MPa) below f'_c should be 1 in 100 or less. In this case:

$$f_{(cr)} = f'_c - 500 + t\,\sigma, \quad \text{(U.S. customary units)}$$

$$= f'_c - 3.45 + t\,\sigma, \quad \text{(S.I. units)}$$

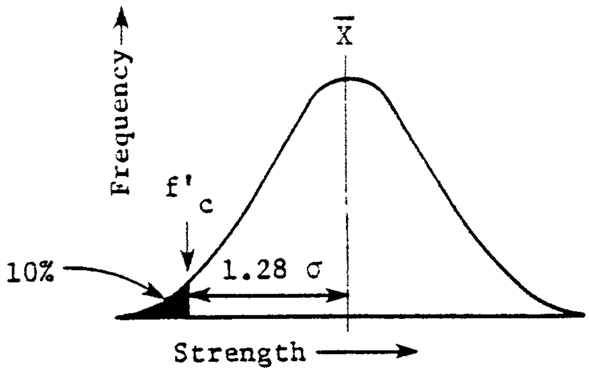

Figure 1. Schematic representation of population characteristics.

where

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

The fourth criterion given by ACI 214 is that there is a certain probability that a random individual strength test will be less than a certain percentage of f'_c. This is often considered as a probability of 1 in 100 that a strength test will be less than 85% of f'_c. That is

$$f_{(cr)} = .85\, f'_c + t\,\sigma$$

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 lb.in.^{2} (2.76 MPa), for poor control; it is assumed to be 800 lb./in.^{2} (5.52 MPa).

Assume A-4 concrete, f'_c = 4,000 lb./in.^{2} (27.58 MPa).

For good control σ = 400 lb./in.^{2} (2.76 MPa)

Criterion 1 $f_{(cr)}$ = 4,000 + 1.28 x 400 = 4,512 (US Customary Units)
= 27.58 + 1.28 x 2.76 = 31.11 (SI Units)

Criterion 2 $f_{(cr)}$ = $4{,}000 + \frac{2.33 \times 400}{\sqrt{3}}$ = 4,538 (US Customary Units)
= $27.58 + \frac{2.33 \times 2.76}{\sqrt{3}}$ = 31.29 (SI Units)

Criterion 3 $f_{(cr)}$ $= 4{,}000 - 500 + 2.33 \times 400 = 4{,}432$ (US Customary Units)
$= 27.58 - 3.45 + 2.33 \times 2.76 = 30.56$ (SI Units)

Criterion 4 $f_{(cr)}$ $= 0.85 \times 4{,}000 + 2.33 \times 400 = 4{,}320$ (US Customary Units)
$= 0.85 \times 27.58 + 2.33 \times 2.76 = 29.79$ (SI Units)

For poor control σ = 800 lb./in.^{2} (5.52 MPa)

Criterion 1 $f_{(cr)}$ $= 4{,}000 + 1.28 \times 800 = 5{,}024$ (US Customary Units)
$27.58 + 1.28 \times 5.52 = 34.64$ (SI Units)

Criterion 2 $f_{(cr)}$ $= 4{,}000 + \frac{2.33 \times 800}{\sqrt{3}} = 5{,}076$ (US Customary Units)
$= 27.58 + \frac{2.33 \times 5.52}{\sqrt{3}} = 35.0$ (SI Units)

Criterion 3 $f_{(cr)}$ $= 4{,}000 - 500 + 2.33 \times 800 = 5{,}364$ (US Customary Units)
$27.58 - 3.45 + 2.33 \times 5.52 = 36.98$ (SI Units)

Criterion 4 $f_{(cr)}$ $= 0.85 \times 4{,}000 + 2.33 \times 800 = 5{,}269$ (US Customary Units)
$= 0.85 \times 27.58 + 2.33 \times 5.52 = 36.33$ (SI Units)

From these examples it is seen that for the same level of control (same σ), the differences between the averages required by all criteria are not very large. However, when the standard deviations are different, the averages for acceptable concrete are significantly different. Thus, under a statistical system, a contractor with poor control having to supply concrete with a higher average than he normally attains under the present system would most likely be required to use a higher cement factor than he now uses or, alternatively, more expensive aggregates than he now uses. This would place him at a distinct disadvantage in relation to a contractor with good control who could continue to use his usual mix design 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.

A major 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.[4]

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 structures. 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.

It must also be kept in mind that all statistical 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 is wrong with the scale, or somebody dumps fly ash instead of cement into 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 production. 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.

HIGHLIGHTS OF STATES' STATISTICALLY BASED SPECIFICATIONS FOR HYDRAULIC CEMENT CONCRETE

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 or developing specifications based on statistical probabilities were reviewed. It was found that relatively few states have made extensive use of statistical concepts in their specifications for hydraulic cement concrete. While no attempt was made to determine all the states that may have experimentally tried such specifications, copies of the specifications in use in 1983 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. These are believed to include essentially all the various systems now under consideration. The highlights of these specifications are summarized in Appendix A.

Each of these agencies have applied statistical procedures for judging the acceptability of the concrete, but 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 includes both air content and strength results in determining partial payments in its specification for base concrete. However, this specification has not yet been used for a construction project. 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 the major concern is with structural and incidental concrete, especially 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 1981. Contracts requiring less than 50 yd.^{3} (38 m^3) 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 yd.^{3} (76 m^3) of concrete. At this frequency of testing, only 21 of 76 (27.6%) projects in 1980 and 9 of 67 (13.4%) in 1981 would have provided 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 high 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.

Number of Concrete Producers

Essentially all structural concrete is supplied by ready-mix concrete producers. Approximately 110 such producers operating over 200 separate plants 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.

TABLE 1

Number and Size of State Contracts
Involving Portland Cement Concrete
1980 and 1981

	Quantity of Concrete — Cubic Yards[a/]					
	50-99	100-299	300-499	500-1,000	>1,000	
Date	Number of Contracts					TOTAL
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
TOTAL — YEAR	8	18	17	12	21	76
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
July		3	2	2		7
August	1	2	4			7
September		1	3			4
October	2	5	3	1	1	12
November		3	1	1	3	8
December	1	1		1	3	6
TOTAL — YEAR	6	24	18	10	9	67

a/ 1 cubic yard = 0.76 cubic metre.

Similar trends have continued through 1981 and 1982. In 1982, 32 plants produced A3 concrete, 19 produced A4 concrete, and 12 produced both classes.

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 appeared that a continuous acceptance plan similar to that used as a special provision by Region 15 of the FHWA (see Appendix A) 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 it was concluded that good inspection would 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.

Following the initial recommendations for revision of the specifications based on the Region 15 FHWA approach, guidelines were prepared for simulating the use of the proposed requirements in highway projects during the 1982 construction season. At the same time a study of historical data stored on computer tapes by the Data Processing Division was conducted. The statistical significance of the acceptance plan was also further analyzed. The findings of these studies and analyses are discussed in the following sections.

EXAMINATION OF HISTORICAL QUALITY ASSURANCE DATA FOR PORTLAND CEMENT CONCRETE

The Virginia Department of Highways and Transportation maintains computerized records of quality assurance test data for portland cement concretes. These records include the source and amounts of each of the ingredients in the concrete, the ready-mix producer, the project and location on which the concrete was placed, and the results of tests for slump, air content, and the compressive strength of test cylinders. The strength tests are made after 14 days, with the concrete being considered acceptable if the strengths of the test cylinders equal or exceed 0.85 times the 28-day strength requirement.

Even though these 14-day data are not suitable for accurately simulating acceptance on the basis of 28-day tests under the suggested specification, the records for selected producers were examined to determine if a "typical" standard deviation could be estimated for each producer and the extent to which all concrete supplied under a single contract could be treated as a single lot and also the degree to which the 14-day test results would indicate compliance to the proposed specification using the usual assumption that the 14-day strengths are 85% of 28-day strength. The selected data are given in Tables 2 and 3, respectively. To avoid confusion only values based on U. S. customary units are included in these tables.

A case-by-case discussion follows:

A3 Concrete — Table 2

Case 1 (Producer 110)

This producer supplied material on a single contract. Installation began on February 9, 1981, and ended December 31, 1981. During this period 20 samples were taken. The average 14-day strength was 4,853 lb./in.^{2} (33.24 MPa) with a standard deviation of 597 lb./in.^{2} (4.09 MPa).

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TABLE 2

Characteristics of A3 Concrete Furnished to VDHT in 1981 by Selected Producers

Job No.	No. Samples	Time Period Covered	Range of Slump inches[a]	Air Content Average %	Air Content Std. Dev. %	14-Day Strength Average lb./in.[2b]	14-Day Strength Std. Dev. lb./in.[2b]	Minimum Allowable 14-day strength,[b,c] lb./in.[2]
Producer 110								
1	20	2/09 - 12/23	1.75 - 3.75	6.4	0.93	4,853	597	3,187
All 1981[d]	20		3.1 avg., 0.68 σ	6.4	0.93	4,853	597	3,187
Producer 501								
1	3	1/15 - 11/16	3.0 - 3.25	6.1	0.36	3,882	645	3,317
2	7	5/14 - 8/27	2.75- 4.0	6.2	0.94	3,756	316	2,894
3	7	7/24 - 10/27	3.0 - 3.75	6.2	1.00	4,115	531	3,128
4	3	9/23 - 10/30	3.25-3.50	6.8	0.40	3,575	313	2,891
5	18	2/24 - 10/16	2.50-4.0	6.5	0.68	3,842	293	2,869
6	5	3/04 - 6/16	3.0 - 3.5	6.5	0.72	3,928	527	3,123
7	6	7/21 - 10/30	2.5 - 3.5	5.6	0.91	3,725	344	2,924
8	5	1/22 - 7/23	1.5 - 3.75	5.8	0.45	4,640	660	3,365
9	5	3/25 - 5/22	2.3 - 4.25	6.1	0.68	4,085	485	3,078
10	5	4/02 - 12/02	3.0 - 3.5	5.9	0.74	4,138	553	3,152
11	4	5/01 - 8/04	3.0 - 3.5	6.2	0.28	3,784	320	2,898
Total	64	1/15 - 12/02	1.5 - 4.25	6.2[e]	0.69[f]	3,951[e]	415[f]	3,002
All 1981[d]	68		3.3 avg., 0.62 σ	6.1	0.77	3,897	440	3,028
Producer 512								
1	1	6/19	4.0	6.2	--	2,880	--	
2	2	2/27 - 5/07	2.5 - 3.5	5.75	--	4,155	--	
3	1	5/11	2.25	6.0	--	3,995	--	
4	1	5/18	2.50	6.1	--	4,060	--	
5	2	6/05 - 7/13	3.0 - 3.75	6.5	--	2,770	--	
6	1	6/08	3.5	5.9	--	2,995	--	
7	1	6/17	3.25	6.1	--	3,115	--	
8	2	8/28 - 9/09	3.5 - 4.0	6.9	--	2,623	--	
9	1	9/29	2.5	6.2	--	3,965	--	
10	1	5/29	3.0	6.5	--	4,265	--	
Total	13			6.1[e]	0.99[f]	3,409[e]	733[f]	
All 1981[d]	13					3,413		3,491
Producer 521								
1	3	7/14 - 8/26	3.5 - 3.5	6.2	0.50	3,621	517	3,112
2	5	2/25 - 3/17	3.25-3.5	6.6	0.08	5,003	686	3,399
3	1	5/26	3.25	6.4	---	3,275	---	
4	2	4/13 - 4/22	3.25-4.50	7.1	---	4,105	---	
5	2	5/08 - 5/22	2.75-3.25	6.0	---	3,530		
6	2	8/27 - 10/19	3.0 -3.5	6.0	---	3,777	---	
All 1981[d]	16	--	3.4 avg., 0.52 σ	6.1[e]	0.56[f]	4,187[e]	867[f]	3,757
Producer 702								
1	32	1/07 - 10/13	2.5 - 4.75	6.0	0.67	4,113	559	3,158
2	25	3/05 - 9/04	3.0 - 4.34	6.1	0.58	4,220	490	3,083
3	7	2/20 - 5/08	3.0 - 3.75	6.4	0.34	3,994	763	3,551
4	3	1/22 - 4/27	3.25 - 4.0	5.7	0.35	3,983	837	3,697
5	3	6/11 - 8/28	2.5 - 3.5	5.6	0.32	3,960	156	2,720
6	4	4/29 - 11/22	3.25- 4.5	6.1	0.52	3,696	397	2,982
7	6	3/23 - 10/22	2.5 - 4.5	5.5	0.65	4,315	363	2,945
Total			2.5	6.0[e]	0.57[f]	4,117[e]	490[f]	3,083
All 1981[d]	98		3.4 avg., 0.44 σ	5.9	0.74	4,197	627	3,282
Producer 803								
1	3	7/27 - 9/25	2.0 - 3.5	6.3	0.16	4,446	810	4,154
2	1	1/20	3.0	4.0	---	4,758		
3	1	6/12	4.0	5.0	---	3,324		
All 1981[d]	5			5.6[e]	0.89[f]	4,501[e]	968[f]	

1/ Based on proposed specification —
When standard deviation is above 571 = [2,400 + 2.33 x std. dev.] x .85
" " " " below 571 = [3,000 + 1.28 x std. dev.] x . 85

2/ Weighted average

3/ Pooled standard deviation

4/ Total 1981 production treated as single population

This average was substantially higher than the minimum required under the proposed specification, 3,187 lb./in.^{2} (21.83 MPa), if it is assumed that the standard deviation at 28 days is the same as the 14-day value.

Case 2 (Producer 501)

This producer supplied a product that was sampled 68 times during the year. Under the proposed specification, the 11 projects involved would be classed as lots. The number of samples taken for each lot varied from 3 to 18. Standard deviations for the lots varied from 293 lb./in.^{2} (2.01 MPa) to 669 lb./in.^{2} (4.58 MPa). The pooled standard deviation was 415 lb./in.^{2} (2.84 MPa) and the weighted average was 3,951 lb./in.^{2} (27.06 MPa). Treating all concrete as a single lot indicates an average of 3,897 lb./in.^{2} (26.69 MPa) and a standard deviation of 440 lb./in.^{2} (3.01 MPa). All strength values for this producer's concrete were well above the minimum required by the proposed specification.

Case 3 (Producer 512)

This producer's product was sampled 13 times. However, 10 jobs were involved with no job being sampled more than twice. The overall standard deviation of the test results (a test result being the average of two 6 x 12 in. [150 x 300 mm] cylinders for each sample) for all samples for this producer was 733 lb./in.^{2} (5.05 MPa) and the average 14-day strength was 3,413 lb./in.^{2} (23.53 MPa). None of the sample concrete had 14-day strengths less than 85 percent of the 28-day requirement — 2,400 lb./in.^{2} (16.55 MPa). Because so few samples were available from a given job a pooled standard deviation could not be determined.

Case 4 (Producer 521)

This producer had his product tested for strength 16 times and 6 jobs were involved, only 2 of which were sampled more than twice. There was considerable variation in the average strengths from job to job, which results in a very high apparent standard deviation if all samples were treated as a single population. Strength results for each job were well above requirements.

Case 5 (Producer 702)

This producer's product was tested 98 times. Seven projects were involved, 2 of which were large — one involving 32 samples and the other 25 samples. For the large jobs the standard deviations were 559 lb./in.^{2} (3.85 MPa) and 490 lb./in.^{2} (3.38 MPa), which are indicative of good control. However, small lots had standard deviations varying from 156 to 837 lb./in.^{2} (1.08 to 5.77 MPa). Since only 3 samples were taken in each of these cases, the difference in the estimate of standard deviation is most likely a result of the small sample size rather than true differences in variability of the concrete production.

Case 6 (Producer 803)

This producer's product was sampled 5 times and 3 projects were involved. One sample representing a single lot had significantly lower strength than the other two, and this led to an apparently large standard deviation when all the results were treated as a single population.

A4 Concrete — Table 3

Case 7 (Producer 123)

Only 4 samples of this producer's product were tested, and each was on a different project. Consequently, no computation of the standard deviation could be made on a project basis. Overall the 4 samples had a standard deviation of 816 lb./in.^{2} (5.63 MPa), which is probably not an accurate estimate of the variability of this producer's product.

Case 8 (Producer 407)

This producer's product was sampled 9 times. Two jobs were involved. On both jobs the strength values were above the minimum requirement of the present specification, but below the minimum average strength required by the proposed specification.

Case 9 (Producer 512)

This producer's product was sampled 12 times during the year. Five small jobs were involved. The average was 4,685 lb./in.^{2} (32.30 MPa) and the standard deviation, counting all as one lot, was 533 lb./in.^{2} (3.68 MPa). Standard deviations varied from 275 to 912 lb./in.^{2} (1.90 to 6.29 MPa).

TABLE 3

Characteristics of A-4 Concrete Furnished to VDHT in 1981 by Selected Producers

Job No.	No. Samples	Time Period Covered	Range of Slump,[a] inches	Air Content Average, %	Air Content Std. Dev., %	14-Day Strength Average, lb./in.^{2}	14-Day Strength Std. Dev., lb./in.^{2}	Minimum Allowable 14-day strength, lb./in.^{2} [b,c]
Producer 123								
1	1	5/12	4.0	4.1	---	5,720	---	4,037
	1	6/03	3.5	5.2	---	4,150	---	4,037
	1	6/23	4.0	5.6	---	3,335	---	4,037
	1	5/01	3.75	4.2	---	4,625	---	4,037
All 1981[d]	4		Avg. 3.8	4.8[e]	0.64[f]	4,345[e]	316[f]	4,270
Producer 407								
1	5	3/26 - 4/28	2.37 - 3.75	6.5	0.60	3,962	287	4,037
2	4	8/28 - 10/29	3.25 - 3.5	5.7	0.87	3,655*	403	4,037
Avg. Jobs				6.1	0.68	3,826	.320	4,037
		* One low value 2,310 not used in average. Coring indicated concrete was satisfactory						
All 1981[d]	9		3.1 avg., 0.39 σ	6.0[e]	0.78[f]	4,113[e]	1,145[f]	4,270
Producer 512								
1	3	6/18 - 8/10	3.5 - 3.75	7.0	0.44	3,972	275	4,037
2	2	5/16 - 7/16	3.0 - 3.0	6.2	---	5,100	---	4,037
3	2	2/26 - 6/03	3.25 - 4.0	5.8	---	4,630	---	4,037
4	3	1/22 - 4/02	2.5 - 3.25	6.3	0.91	4,735	579	4,037
5	3	7/02 - 9/09	0.5 - 3.75	6.4	0.80	4,382	912	4,037
All 1981[d]	13		3.2 avg., 0.36 σ	6.4[e]	0.34[f]	4,685[e]	533[f]	
Producer 703								
1	8	3/13 - 10/21	2.5 - 3.5	6.5	0.95	4,236	441	3,380
2	7	4/08 - 11/19	2.0 - 4.0	6.4	0.43	4,189	543	3,991
3	3	5/21 - 5/21	3.0 - 3.5	6.3	1.03	4,592	88	4,037
4	5	9/03 - 11/17	3.0 - 3.75	6.1	0.76	4,340	92	4,037
5	3	9/15 - 9/15	2.75 - 3.0	6.1	0.43	4,188	407	4,037
6	24	5/07 - 12/30	2.5 - 4.0	6.5	0.76	4,138	450	3,890
Total	50	3/13 - 12/30	2.0 - 4.0	6.4[e]	0.72[f]	4,211[e]	408[f]	3,844
All 1981[d]	52		3.3 avg., 0.63 σ	6.4	0.33	4,215	487	3,930
Producer 803								
1	3	3/24 - 8/05	3.5 - 4.0	5.7	1.10	3,765	211	4,037
2	1	8/19	3.0	5.3	---	5,688	---	4,037
3	1	8/07	2.0	5.3	---	3,555	---	4,037
All 1981	5		3.2 avg., 0.76 σ	5.5		4,108	900[f]	4,037
Producer 811								
1	2	6/04 - 6/16	3.25 - 3.50	6.7	---	3,765	---	4,037
2	1	8/26	2.75	7.0	---	4,376	---	4,037
All 1981[d]	3			6.8[e]	0.17[f]	3,969[e]	323[f]	4,037

[a] 1 inch = 25.4 mm

[b] 1 lb./in.^{2} = .00689 MPa

[c] Requirements for 100 percent pay factor based on proposed specification:

$n \leq 5 = [3{,}000 + 1.28\ (586)] \times .35$

$n > 5 = [3{,}000 + 1.28\ (\text{Std.dev.})] \times .85$

(n = 6 to 29 use min. std. dev. of 400 lb./in.^{2} and max. std. dev. of 800 lb./in.^{2})

[d] Total 1981 production treated as single population

[e] Weighted average

[f] Pooled standard deviation

Case 10 (Producer 703)

A total of 52 samples were taken from this producer's product. Six jobs were represented, with the minimum standard deviation being 88 lb./in.^{2} (0.61 MPa) and the maximum 543 lb./in.^{2} (3.74 MPa).

Case 11 (Producer 803)

This producer had only 6 samples tested during the year. Strengths were above the minimum required by the present specification, but in two cases were below that required by the proposed specification.

Case 12 (Producer 811)

This producer had 3 samples tested. The standard deviation for the 3 was 323 lb./in.^{2} (2.23 MPa). The average of two test results (each result being an average of two 6 x 12 in. [150 x 300 mm] cylinders) for 1 job was below that required by the proposed specification.

Conclusions from Historical Data

The long time span from the beginning of a project to its completion, as indicated by the data for all producers now filed in the computer, indicates that treating all concrete furnished under a contract as a single population might be questionable from a statistical viewpoint. However, even when the total contract is considered a single lot, only a few producers had their products tested a sufficient number of times to provide enough data for good estimates of averages and standard deviations of the lot. As previously stated, these 14-day strength data cannot be used to simulate direct application of the proposed specification. However, they do show that most producers provide A3 concretes with strengths well above the minimum limits assuming the 14-day strength is 0.85% of the 28-day strength. Only a few A3 concretes meeting present specifications would not comply with the requirements for 100% pay factor under the proposed specification. All A4 concretes had adequate strengths based on present requirements but for a number of projects the concrete had projected average strength values lower than those required for 100% pay. Whether or not the actual 28-day test results would have complied to the proposed specifications is not known.

From this limited study, it was concluded that further evaluations of historical data for the purposes of this project would not provide significant information relating to the standard deviation for a given producer.

SIMULATION STUDIES

During the 1982 construction season, district materials engineers were asked to make special tests to simulate the use of the initially proposed specification. The special instructions prepared for this simulation are included as Appendix B to this report. Information was provided for 1 project by the Staunton and for 4 projects by the Richmond District. These results are shown in Table 4. Strength tests conducted for all these projects showed full compliance with the limits that would have been in effect under the initially proposed specification. It is also shown that full compliance to the presently proposed specification would have resulted in all cases, even though the required average for strength in some cases would have been increased because of the use of minimum rather than actual standard deviations.

Under the initially proposed recommendation, a reduced payment would have been assessed because of the large standard deviation based on only 3 samples for producer B even though the average air content was 6.7%, very close to optimum. Obviously a reduction in payment in this situation cannot be justified. This problem is avoided by the presently proposed system which applies a reduction in payment only if the average air content is more than 0.5% below the midpoint of the allowable range. No reduction in pay factor would have occurred for 3 of the 5 simulated projects, but some reduction would have resulted for 2 of the A4 concrete projects where the average air contents were 5.8% (Project 3) and 5.9% (Project 4), respectively. A review of the historical data for all producers' production in 1981 shows that the overall average air content for each producer was less than 6.0% for A4 concrete 15 out of 46 times and less than 5.5% for A3 concrete 10 out of 47 times. In the 1982 construction season the producer's average air contents for A4 concrete was less than 6.0% 4 out of 15 times. Similarly the producer's averages were less than 5.5% for A3 concrete 2 out of 32 times. These results most likely reflect current custom rather than indicate any difficulty in meeting requirements for a slightly higher overall average air content.

TABLE 4

SUMMARY OF PROJECTS SIMULATING USE OF PROPOSED SPECIFICATIONS

Project	1	2	3	4	5
Type Concrete	A3	A4	A4	A4	A4
District	Staunton	Richmond	Richmond	Richmond	Richmond
Concrete Producer	A	B	C	D	D
No. Samples, n.	14	3	17	8	7
Avg. 14-day Strength, $lb./in.^2$	3,888				
Std. Dev. (14-day) $lb./in.^2$	329				
Avg. 28-day Strength, $lb./in.^2$	4,555	5,719	4,636	5,448	4,745
Std. Dev. (28-day) $lb./in.^2$	355	206	161	551	109
Ratio 14 day/28-day	.854				
Initial Recommendation:					
Required Avg. 28-day strength	3,454	4,264	4,206	4,705	4,140
Producer Correction C_{pr}	156		64	321	68
Corrected Average, $lb./in.^2$	3,298		4,142	4,384	4,072
Quality Level for Strength	100%	100%	100%	100%	100%
Pay Factor for Strength	1.0	1.0	1.0	1.0	1.0
Present Recommendation:					
Required Average 28-day strength	3,512	4,750	4,512	4,705	4,512
Quality Level for Strength	100%	100%	100%	100%	100%
Pay Factor for Strength	1.0	1.0	1.0	1.0	1.0
Air Content, Average	5.9	6.7	5.8	5.9	6.5
Air Content, Std. Dev.	0.86	1.0	.66	.67	.68
Initial Recommendation:					
Quality Level for Air Content, percent	100%	86.6%*	100%	100%	100%
Pay Factor for Air	1.0	.976	1.0	1.0	1.0
Total Pay Factor	1.0	.976	1.0	1.0	1.0
Present Recommendation:					
Min. Avg. for 1.0 pay factor	5.5	6.0	6.0	6.0	6.0
Pay Factor	1.0	1.0	0.94	0.97	1.0
Total Pay Factor	1.0	1.0	0.94	0.97	1.0

*Since n=3, the standard deviation of 1.0 is likely high and a reduction in pay factor in this case would not be justified. If standard deviation is assumed to be 0.70, no reduction in pay factor would be indicated.

STATISTICAL SIGNIFICANCE OF PROPOSED REVISIONS

Both the initially proposed acceptance plan for portland cement concrete and the revised proposal were examined to determine the effect of the statistical procedures on the acceptance levels for concrete and to assess their impact from an engineering point of view. This study revealed the need for reconsideration of some of the concepts involved in the initial proposal.

The first problem is with the concept that all materials are acceptable when less than 10% of the population is below f'_c without establishing a minimum value for single results. Statistically, for a truly normal distribution, 1% of values in the distribution will be below 2.33 times the standard deviation. This means that if the assumed normal distribution holds rigidly, A4 concrete with a "true" average strength of 4,750 lb./in.^{2} (32.75 MPa) and a true standard deviation of 800 lb./in.^{2} (5.52 MPa) could have 1% of its strengths as low as 2,886 lb./in.^{2} (19.90 MPa). However, from the engineering viewpoint, the rigid applicability of normal distribution for the outlying regions is questionable. It is more likely that conditions that might result in such extreme values would be detected by visual inspection and such concrete would not be placed in the structure.

Another justification for accepting the theoretical risk of a small percentage of strength values below f'_c is the fact that, according to theory, there is a much higher percentage of strength values above f'_c; that is, if 10% are below f'_c, 90% will be above f'_c. There is also a corresponding probability (9 to 1) that high values rather than low values will occur at critical areas. Thus, under normal conditions, the 10% low values would not result in an actual strength of the structure below f'_c.

In the specification as now proposed protection against too low strengths for single batches of concrete is attained by incorporating a secondary requirement in the specification which states that no test result (average of 3 cylinders) be more than 500 lb./in.^{2} (3.45 MPa) below f'_c.

The Producer's Risk

Initially, consideration was given to the application of a correction to the average of the test results to reduce the producer's risk of having acceptable material subjected to a reduction in payment. This system is used by FHWA Region 15.

That correction is based on establishing the 95% confidence interval for the average of the test results. That is, given an average of n results with a given standard deviation, it can be stated that there is a 95% probability that the true average will be between the limit of

$$\bar{X} - \frac{1.65\ \sigma}{\sqrt{n}} \quad \text{and} \quad \bar{X} + \frac{1.65\ \sigma}{\sqrt{n}}.$$

Thus, the FHWA special provision added a "producer's correction" equal to $1.65\ \sigma/\sqrt{n}$ to the average of the test results for the purposes of establishing an adjusted average to be used as the basis for computing the pay factor. This procedure, however, results in providing a greater correction for larger standard deviations, thus, in effect, rewarding the concrete producer for poor quality control — an undesirable situation. Consequently, it was decided that the producer's correction not be applied. It is believed that present industrial practices in the state are such that concrete producers normally take into account the risks involved in a small amount of testing and that decisions should be based on actual averages of test data rather than adjusted values based on theoretical computations.

Acceptable Averages for Strength and Application of Reduced Pay Factors

Ideally under the proposed specification, the acceptable average of a product should be dependent on the standard deviation of the population of test results represented by that average. However, a difficulty is encountered in determining a proper estimate of the standard deviation. When the estimate of the standard deviation indicated by the test results themselves is used, it is subject to large uncertainties if the number of test results are low, and the assumption that the sample standard deviations adequately represents the population standard deviation may not be valid.

Because of the uncertainties concerning the estimates of the standard deviation, the finally recommended specification recognizes three situations for acceptance of concrete production. These are:

1. When the number of tests made is 5 or less, the standard deviation for all producers is assumed to be 586 lb./in.^{2} (4.04 MPa) and all strength requirements are computed accordingly. This value was chosen since it approximates the average standard deviation for statewide records for all

concrete production for the state and provides for a requirement that the average strength be 750 lb./in.^{2} (5.17 MPa) above f'_c.

2. When the number of tests made is more than 5 and a pooled standard deviation of 30 or more samples is not available, the standard deviation of the sample is used, except that a minimum value of 400 lb./in.^{2} (2.76 MPa) and a maximum value of 800 lb./in.^{2} (5.52 MPa) are used.

3. When 30 or more test results are available, a pooled standard deviation is used based on the sample results, plus a sufficient number of the latest results from earlier production with the same mix design and materials to provide a total of 30 tests for determining the standard deviation.

While this approach does not provide for establishing constant risks and uniform statistical acceptance probabilities for either the state or the concrete producer, it is believed equitable from an engineering viewpoint.

In the real world of concrete production, the true value (in the statistical sense) of the average concrete strength is not known. Only the average of a limited number of test results is available as an estimate of that true value. Statistically, the estimate obtained from the test results has an increasing probability of representing the true value as the number of samples used to establish the average increases. The probability that an error is being made also decreases as the variability of the test results, as measured by the standard deviation, decreases. While these are all principles that must be considered in establishing an acceptance procedure, the major concern of the concrete producer is whether or not the average of the test results indicates full compliance with the specification so that he receives no reduction in the pay factor. He is also concerned with the amount of reduction in pay factor when borderline results are obtained.

The pay factor for strength of the concrete is determined in the following manner.

From the average of the test results and the computed or assumed standard deviation, s, the quality index, Q, is computed from the equation

$$Q = \frac{\overline{X} - f'_c}{s},$$

where

Q = the quality index,

$\overline{X}$ = the average of the strength test results, and

s = the applicable assumed or computed estimate of the standard deviation.

The quality index, Q, is then used to determine the quality level, QL, which is the percentage of the population distribution above the designated low limit, f'_c. Alternatively, the percent defective, which is the percentage of the population distribution below the designated low limit f'_c, can be used.

For small numbers of samples, the relation of the percent defective to the quality index varies with the number of samples, n, involved; thus different Q tables for different numbers of samples are available. However, when n is equal to or greater than 30, the normal distribution curve may be used. For this situation, $Q = z$ and, s, the computed estimate of the standard deviation, is essentially equal to the true standard deviation of the population. As will be discussed later, the normal distribution curve is used in the proposed specification to determine the QL from Q.

The pay factor for strength is then determined as

$$PFS = (QL + 10)/100,$$

where

QL is the percentage above the minimum design strength.

Thus, any production having a QL of 90% or greater receives 100% pay. The pay factor is reduced on a straight-line basis for production with a quality level between 60% and 90%. The lower limit is somewhat arbitrarily selected as the point at which the quality of the concrete may be seriously questioned, and thus the concrete is rejected or an investigation is made by coring the structure. If core strengths are satisfactory, the concrete may be accepted on the basis of such cores. In this case, the pay factor is based on an adjusted strength equal to the core strength divided by 0.85.

Under the proposed specification, when the number of samples tested is 5 or less, the standard deviation is assumed to be the same (586 lb./in.^{2} [4.04 MPa]) for all production of concrete.

This has the effect of establishing a constant value of the average for which a 100% pay factor is obtained (f'_c + 750 lb./in.^{2} [5.17 MPa]). It is further assumed that the percent within limits or the quality level can adequately be estimated from the normal distribution curve. Thus, for this situation the pay factor becomes a function of the average of the test results. Under these circumstances the risks that an incorrect decision is being made will vary according to whether the number of tests made is 2, 3, 4, or 5. It is recognized that the use of the normal distribution curve for the determination of the quality level with so few samples is not theoretically correct. However, a comparison of the results obtained using the normal distribution with the results obtained using the program for non-central t distribution developed by the New Jersey Department of Transportation, which is theoretically more accurate, shows only small differences in pay factors for the same average strengths. These differences are illustrated in Table 5 and Figure 2. Since the pay factor established represents a decision based on general engineering judgement, the use of factors based on the normal distribution curve has been recommended. This provides a simplified approach that is more easily understood by those with only a limited knowledge of statistical principles. Thus, the solid line in Figure 2 can be used to determine the pay factor for all concrete lots based on the average of 5 or fewer samples.

For larger jobs, estimates of the standard deviation are based on the sample results or on pooled values based on a combination of the sample results plus previous production using the same materials and mix design. In these cases, the pay factor for the same average of test results will vary depending on the standard deviation. However, it has been demonstrated by a large volume of tests on all types of concrete that batch-to-batch variability is not likely to be less than 400 lb./in.^{2} (2.76 MPa). Accordingly, this value is selected as the minimum standard deviation used in the computation of the pay factor. Likewise, the variability in a properly adjusted and controlled plant should not greatly exceed 800 lb./in.^{2} (5.52 MPa). Thus, this value is established as the maximum value used for computing the pay factor. Table 6 provides a comparison of the differences obtained in pay factors between the non-central t program n = 10 and the normal distribution. As indicated, the differences are very small, and again the use of the normal distribution for determining the quality level is recommended in order to simplify the specification.

Figure 3 illustrates the significant effect the variability of production could have under these conditions. For an average of test results 510 lb./in.^{2} (3.52 MPa) above the minimum design strength, the pay factor could be as low as 84% if the standard deviation were 800 lb./in.^{2} (5.52 MPa) or greater. However, the pay factor would be 100% if the standard deviation were 400 lb./in.^{2} (2.76 MPa) or less. Potential differences of this magnitude provide a significant incentive for good quality control that will be advantageous to both the concrete producer and the Department of Highways and Transportation.

TABLE 5

PAY FACTORS FOR VARIOUS TEST AVERAGES
WHEN STANDARD DEVIATION IS 586 LB./IN.^{2} (4.40 MPa)

Amount by Which the Average of Test Cylinders Exceeds f'_c, lb./in.^{2} 3/	Q 1/	Pay Factors 2/ Non-Central t			Normal Distribution
		n = 3	n = 5	n = 10	
100	0.17	0.647	0.660	0.665	0.667
200	0.34	0.695	0.720	0.729	0.733
300	0.51	0.746	0.779	0.790	0.795
400	0.68	0.800	0.836	0.847	0.852
500	0.85	0.863	0.891	0.899	0.902
600	1.024	0.945	0.944	0.946	0.947
700	1.195	1.000	0.990	1.000	0.984
800	1.365	1.000	1.000	1.000	1.000
900	1.536	1.000	1.000	1.000	1.000
1,000	1.706	1.000	1.000	1.000	1.000

1/ $Q = (\overline{X} - f'_c)/s$

2/ Pay factor = QL + 10, where quality levels are determined from distribution tables based on values of Q. For the normal distribution curve, Q = z.

3/ 1 lb./in.^{2} = 0.006895 MPa

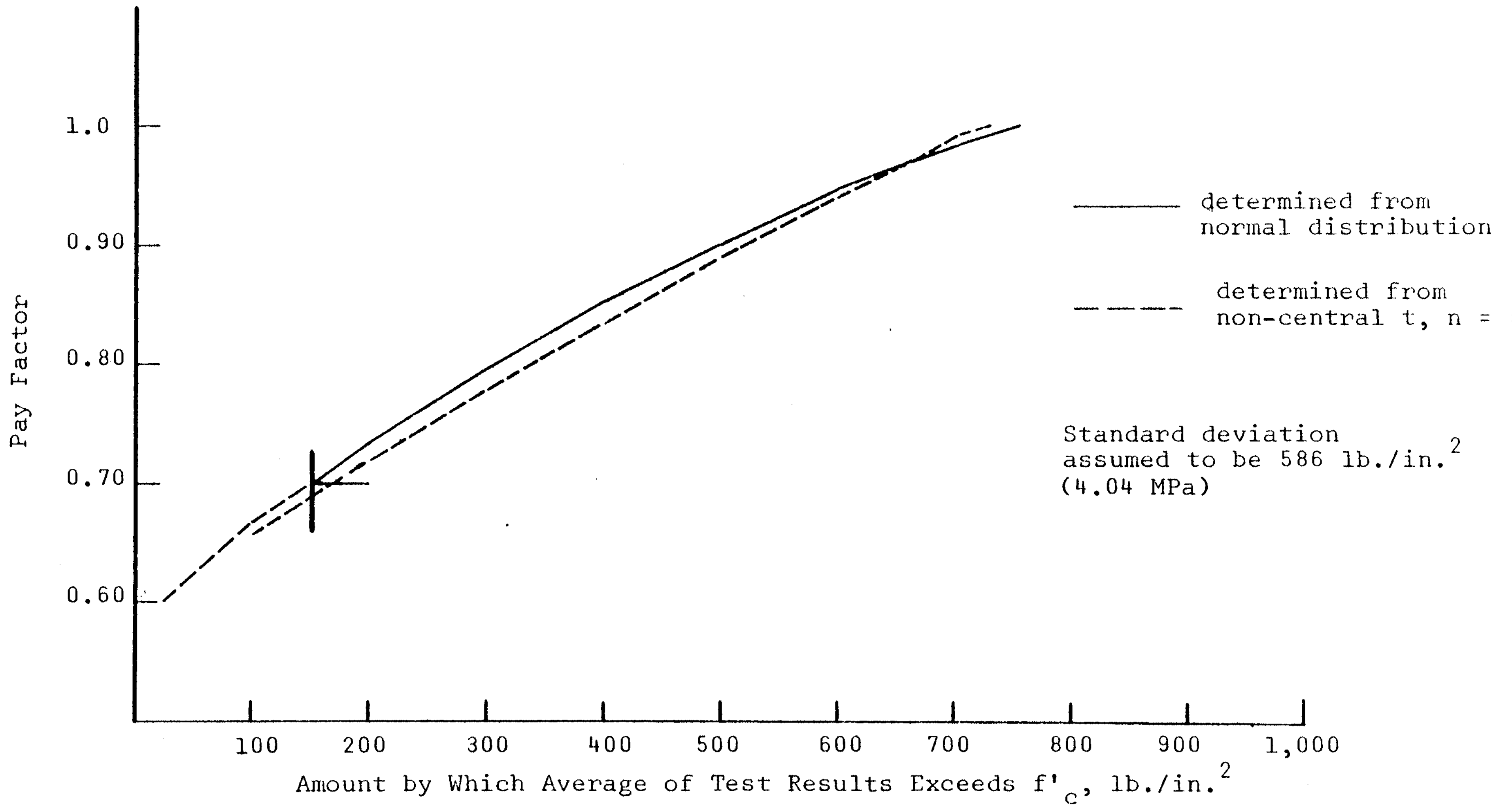

Figure 2. Pay factors for various average test results, applicable when the number of tests is 5 or less. 1 lb./in.^{2} = 0.006895 MPa

TABLE 6

PAY FACTORS FOR VARIOUS TEST AVERAGES WITH STANDARD DEVIATIONS EQUAL TO 400 LB./IN.^{2} (2.76 MPa) AND 800 LB./IN.^{2} (5.52 MPa)

Amount by Which the Average of Test Cylinders Exceeds f'_c, lb./in.^{2} 3/	Pay Factors 2/					
	Std. Dev. = 400 lb./in.^{2} (2.76 MPa)			Std. Dev. = 800 lb.in.^{2} (5.52 MPa)		
	Q 1/	Non-Central t n = 10	Normal Distribution	Q 1/	Non-Central t n = 10	Normal Distribution
100	0.250	0.695	0.699	0.125	0.646	0.650
200	0.500	0.786	0.792	0.250	0.695	0.699
300	0.750	0.869	0.873	0.375	0.741	0.746
400	1.000	0.940	0.941	0.500	0.786	0.791
500	1.250	0.998	0.994	0.625	0.829	0.834
600	1.500	1.000	1.000	0.750	0.869	0.873
700	1.750	1.000	1.000	0.875	0.906	0.909
800	2.000	1.000	1.000	1.000	0.940	0.941
900	2.250	1.000	1.000	1.125	0.971	0.970
1,000	2.500	1.000	1.000	1.250	0.990	0.994
1,100	2.750	1.000	1.000	1.375	1.000	1.000

1/ $Q = (\bar{X} - f'_c)/s$

2/ Pay factor = QL + 10, where quality levels are determined from distribution tables based on values of Q. For the normal distribution curve, Q = z.

3/ 1 lb./in.^{2} = .006895 MPa

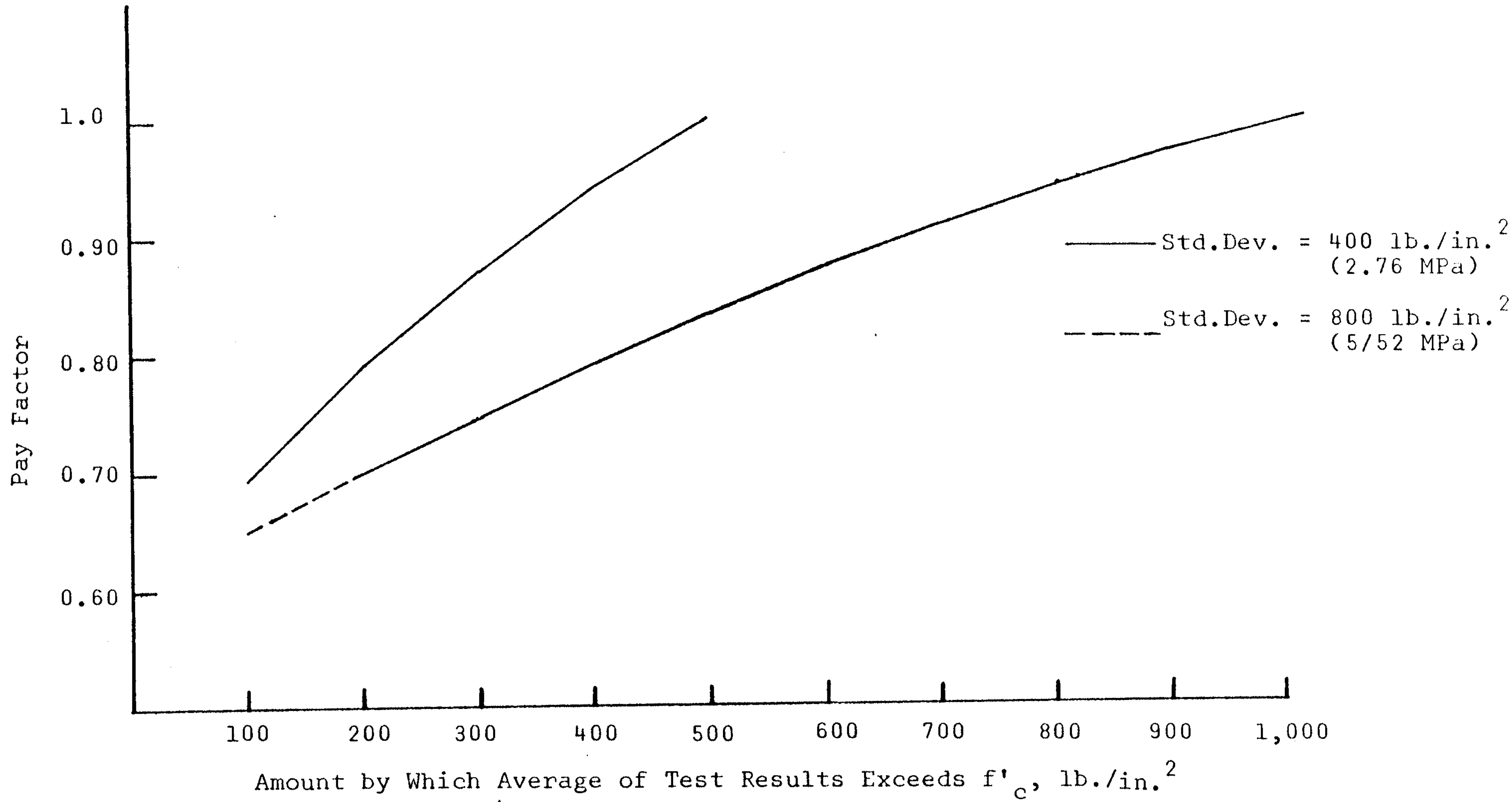

Figure 3. Pay factors for various average test results when standard deviation is minimum value (400 lb./in.^{2} [2.76 MPa]) and maximum value (800 lb./in.^{2}[5.52 MPa]).
1 lb./in.^{2} = 0.006895 MPa

Acceptable Air Entrainment

The simulated results given in Table 3 basing acceptance of air entrainment on the quality level (percent within limits) revealed that this procedure was not feasible for small lots with a limited number of tests. In some cases where only 3 or 4 samples were involved and air contents on the first samples were near the low end of the tolerance range, the air content was adjusted upward as required by good engineering practice. However, this had the effect of indicating a large standard deviation, which on the basis of assuming a normal distribution would indicate relatively high percentages outside the acceptable range when such would not likely be the case since deliberate changes had been made. Accordingly, in the specification now proposed, the decision to place the concrete is made on the basis of individual tests for entrained air being within the tolerance range as at present. However, since it is also the intent of the specification that the average air content be close to the target value, requirements for the average air content are introduced in the proposed revision. This is to be computed from all test results for air content recorded for concretes placed in the structure; the results of tests on rejected concrete would not be included. Minimum acceptable averages established on the basis of engineering judgement are 5.5% for A3 concrete and 6.0% for A4 concrete. Maximum limits on the average air content were not established since the adverse effect of too much air is a reduction in strength, and protection against detrimentally low strengths is obtained by the minimum strength requirements. If the average air content is 1.00% or less below the minimum average, a reduced pay factor for air is computed. The equation for this computation is

$$PFA = .70 + .30\ [\overline{X} - (\overline{X}_{min.} - 1.00)],$$

where

PFA = pay factor for air,

$\overline{X}$ = average of the test result for air, and

$\overline{X}_{min.}$ = the minimum average for the class of concrete involved.

This equation, in effect, establishes the minimum pay factor at 0.70 for concrete having an air content of 1.00% below the minimum and adds back a proportionate amount of the 30% reduction based on the proportionate amount of the 1.00% maximum allowance. (Average air contents are calculated to two decimal places for this purpose.)

With proper inspection average air contents more than 1.00% below the minimums established should not be encountered. However, should this occur, provision is made for examining the hardened concrete in the structure to determine if a durable air void system is present. If examination by ASTM Procedure C457 (linear traverse) shows that the spacing factor, $\bar{L}$, is 0.008 in.$^{-1}$ (0.20 mm^{-1}) or less, the concrete will be allowed to remain in place and a 0.70 pay factor for air will be applied.(6) The reduction in pay factor is believed justified even though suitable durability is indicated by the cores, since the low average air content is indicative of a lower "factor of safety" than would exist with a higher average air content. Should the spacing factor be greater than 0.008 in.$^{-1}$ (0.20 mm^{-1}), the concrete would be susceptible to damage from freezing and thawing if exposed to high moisture conditions and should be replaced or other measures taken to protect the concrete. A case-by-case decision would be needed in such situations.

THE PROPOSED SPECIFICATION

Appendix C is a proposed revision of Section 219 of the Virginia Department of Highways and Transportation Road and Bridge Specifications incorporating the principles discussed in the preceding sections of this report.

Except for testing at 28 days instead of 14 days, the proposed revisions do not greatly change the present inspection and testing procedures. For situations where all present specifications are being met, the quality of the concrete being placed is not likely to change significantly; however, the revisions would establish a situation in which contractors with borderline materials producing concrete with minor deficiencies would be penalized if the strength of their concrete was lower than specified or if the average air contents were too low. 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.

The use of statistical concepts should also result in better knowledge of the initial characteristics of the concrete. Such knowledge would provide a data base for subsequent evaluations of the concrete performance. If these recommendations are adopted, to establish compatibility with the revised specifications, revisions will be required in Chapter 4, Portland Cement Concrete, of the Manual of Instructions, provided inspectors.(7) Recommendations for such revisions are included in Appendix D.

A stated procedure for randomly selecting the load of concrete to be sampled for acceptance strength tests is also recommended as an addition to the Virginia Manual of Test Methods.[3] A proposed draft of such a test method is included as Appendix E.

RECOMMENDATIONS

1. The proposed specification is recommended for immediate adoption and constitutes the final recommendation of the present study.

2. Simultaneously with the adoption of the proposed specification, revisions to the instructions to concrete inspectors provided in Appendix D should be adopted as well as the proposed test method for random selection of concrete batches to be sampled.

3. Prior to the effective date of the revisions, a general explanation of the changes being made in the specification and the means of judging compliance should be provided to all concrete producers having state contracts and state field personnel having responsibilities in this area. This should be accomplished by one-day workshops in several areas of the state.

4. Implementation of these revisions to the specifications should be considered a first step toward specifications that will closely relate to performance and one that will have greater end-result implications.

   Further studies should be initiated to eliminate as much as is possible of the detailed descriptions of equipment and procedures now included in the specifications. This would permit greater flexibility on the part of the contractor and concrete producer to improve their operations. Consideration should be given to the adoption of the ASTM Specification for Ready-Mix Concrete, C-94(6). If this specification is deemed inadequate, any special requirements for Department specifications must be compatible with good practice shown by present ready-mix concrete producers. Concrete for highway construction represents only a small percentage of the volume of their business, thus significantly more restrictive plant requirements would most likely be unenforceable.

5. The feasibility of acceptance on the basis of predicted 28-day strengths obtained by accelerated curing or the maturity concept should be studied. Several states are now using this approach with good results, and minimizing the time lag between placement and final acceptance is a very desirable goal. A rapid procedure would avoid continuation of placement of concrete with unacceptable or borderline characteristics subject to reduced pay factors.

6. The feasibility of using one of the procedures developed for determining cement and water content in concrete before placement should be evaluated. If such equipment can produce relatively accurate results, a way for a truly end-result specification would be opened. The ability to determine the actual water-cement ratio in the concrete before it is placed might also open the way for allowing a contractor to modify his cement factor when quality control is good and strength levels are high. This would provide an excellent incentive for the institution of good quality control by the contractor because his production costs would be reduced. This would also be advantageous to the state by providing high quality concrete of uniform characteristics.

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5. Barros, R. T., R. M. Weed, and J. H. Willenbrock, "Design and Analysis of Acceptance Procedures Based on Percent Defective", (Presented at the 1983 meeting of the Transportation Research Board, Washington, D. C.).

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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.

This procedure was used during the 1980, 1981 and 1982 construction seasons with good results. With minor editorial revisions it is being considered for adoption as a part of the standard procedures for direct federal construction.

GEORGIA

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 an air content 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.

All cement, aggregates, and admixtures must be from approved sources.

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

Prior to the start of construction, the contractor submits the mix design to the Regional Materials Engineer for approval.

Trial mix testing is required with an authorized representative of the state materials engineer present. Arrangements must be made at least 2 weeks before tests are to be conducted.

Required average strengths are determined as in ACI 214, except that statistical computations are based on a population size of 15 or more tests (instead of 30) and (n-1) weighting is used to estimate the standard deviation and coefficient of variation.

When past performance records are available a minimum of 15 consecutive 28-day strength results made within the last year using the same mix design are used to compute the coefficient of variation, which in turn is used to compute the required average strength. If data are not available, a coefficient of variation of 15% is used to compute the required average strength.

Control tests are required on the basis of one randomized sample for each 50 yd.^{3} Tests are made for slump, air content, and compressive strength.

The contractor molds and cures strength specimens for 3 to 7 days and then delivers them to the state laboratory. The project engineer has the responsibility for slump and air content tests.

Concrete is accepted if there is no greater than a 1 in 10 probability that the strength will fall below the specified strength. The average of any 2 companion specimens also must not be less than 80% of the design specified strength, and the running average of any 5 successive tests must not be less than the design specified strength.

The concrete mix design may be modified with approval of the engineer if strengths greatly exceed requirements but a minimum cement factor applies.

The specification does not include provisions for partial payments for noncomplying concrete.

NEW JERSEY

Four classes of concrete are recognized, with a class design strength and a structural design strength indicated for each class as follows:

Class of Concrete	Class Design Strength, psi	Structural Design Strength, psi	Typical Use
P	5,500	5,000	Prestressed Beams
A	4,200	3,000	Bridge Decks
B	3,700	3,000	Pavements
C	3,200	3,000	Foundations

The structural design strength is the value usually designated as f'_c and is the strength required by the designer to assure structural integrity. The class design strength is a higher level of strength specified to obtain other benefits such as impermeability, durability, and abrasion resistance.

In the specification, the class design strength is the limit used to establish the acceptable quality level (AQL), which is defined as 10% below the class design strength for each class of concrete.

The rejectable quality level (RQL) is based on the structural design strength. It is defined as the average strength for which 10% of the concrete would have strengths less than the structural design strength in all classes except Class C. For Class C, the RQL is defined as the average for which 20% of the concrete would have strengths less than the structural design strength.

The contractor establishes the necessary mix designs and prepares trial batches for verification under state supervision. A table is provided to guide the producer in deciding how far above the design strength the target strength should be set for each class. At least one mix must be designed for a target strength 500 psi higher than the maximum value obtained from this table. The over-design guide for establishing the averages a given contractor must equal or exceed is based on the formula

$$\text{Target Strength} \geq \text{Class Design Strength} + 1.282\ S,$$

in which S is the producer's current within-lot standard deviation.

The standard deviation is computed for each producer from acceptance test results and is based on the most recent 10 lots or one month's production, whichever produces the larger sample size. Within-lot standard deviations are pooled across concrete classes to obtain the current value.

Maximum lot sizes are defined as one day's production, 500 $yds.^3$ (300 $yd.^3$ for structures), or 50 truckloads, whichever volume is smallest.

A test result is defined as the average 28-day strength of a concrete cylinder pair. Normally, six tests are performed at random locations within each lot.

Acceptance is based on the percentage of material estimated to fall below the class design strength for each lot. The pay factor (PF) is computed from the formula

$$PF = 102 - 0.2\ PD,$$

and is exactly 100% when the percent defective (PD) is at the AQL of 10% defective. When the estimated percent defective is less than 10%, the pay equation awards small bonuses up to a maximum of 2%.

When single tests fall below limits set in the specification, or the estimated percent defective exceeds limits set for each class of concrete, the lot may be retested by coring or suitable nondestructive means. The agency reserves the right to require removal and replacement of seriously defective concrete.

Air entrainment and slump testing is basically a screening process. These tests are performed at the same rate and on the same loads as the compressive strength tests and, if the test results are not within the specified limits, the concrete is not accepted for use on the project. The present version of the specification contains an experimental feature that permits a single retempering for air entrainment and slump (and subsequent retesting) provided neither parameter is above its upper limit.

OHIO

Ohio has developed a statistical specification for portland cement concrete used in pavement base courses. However, as of January 1983, it was reported that this specification had not been used in actual construction.

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.

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 by the contractor 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:

- $\bar{A}$ — 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 extablished 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 statistical analysis indicates that at least 93% of the concrete has strengths equal to or above the design strength (specification minimum). Also, 99.9% of the concrete must have strengths 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

GUIDELINES FOR SIMULATING STATISTICAL ACCEPTANCE TESTING FOR PORTLAND CEMENT CONCRETE

INTRODUCTION

The proposed revisions of Section 219, Hydraulic Cement Concrete, of the Standard Specifications for Roads and Bridges of the Virginia Department of Highways and Transportation introduce the concept of acceptance on the basis of statistical probabilities, with reduced pay for concrete outside of normal specification limits but not considered to be sufficiently deficient to warrant removal. Under the proposed specification, reduced pay will result, when on a statistical basis, there is more than a 95% probability that more than 10% of the concrete placed in the job is below the minimum requirement for 28-day compressive strength or outside the minimum and maximum limits for the percentage of entrained air.

The system proposed provides for considering all the concrete of a single class made with the same ingredients in a contract as a single lot, except where very large amounts of concrete are involved. The number of samples per lot thus varies with the size of the job. In acceptance a correction is applied to minimize the producer's risk of having acceptable concrete subjected to a reduction in pay. This has the effect of statistically increasing the risk to the state that poorer than indicated concrete will be accepted, but on large lots requiring at least 10 samples the state's risk is reduced. The same risk of accepting poor material exists under present procedures. It is emphasized that under any specification, dependence is placed on good concreting practice and good inspection procedures to assure that inferior concrete is not placed.

Prior to implementation of the new concept, it is desirable to evaluate the proposed revision by its simulated application to projects constructed in the 1982 season. For this simulation several changes in sampling and testing procedures are required. These are explained in the following sections.

INSPECTION AND MONITORING TESTS

Under the revised specifications, there is no significant change in the responsibilities of inspectors with respect to acceptable plant equipment and mixing techniques. Obviously unsatisfactory conditions or improper equipment, materials, and techniques must immediately be called to the attention of the responsible person as in the past. Monitoring of aggregate moisture and water/cement ratios is conducted in the same manner as before. Ultimately, as concrete producers develop improved quality control procedures, it is hoped that the state inspector's involvement in aggregate moisture tests and other quality control tests that are the contractor's responsibility can be minimized.

SAMPLING AND TESTING FOR ACCEPTANCE

A significant change is made in the manner of selecting a truck to be sampled for making strength and other acceptance tests. Such samples will be designated as acceptance samples, and they must be selected by a predetermined system based on random numbers or some other suitable randomizing system. This systematic randomization is extremely important and <u>must</u> be adhered to in order to attain a proper evaluation of the proposed revision. A good procedure to use is described in ASTM D3665. This procedure is published in Part 15 of the ASTM Standards.

Frequency of Sampling

The proposed specification basically establishes the size of a sublot for bridge decks at 50 yd.^{3} and that for structural concrete other than that for bridge decks at 100 yd.^{3}. While some special considerations are included in the proposed specification for small jobs, these are not applicable if the jobs chosen for simulation exceed 150 yd.^{3} for bridge deck concrete or 300 yd.^{3} for other structural concrete.

Randomization Procedures

Randomization should be established to determine the portion of the sublot to be sampled by the use of ASTM D3665, or this can be done by a procedure similar to that used by the Department for other materials in which the percentage of the sublot is determined by drawing numbered discs or washers from a can. The first number drawn represents the first digit of the percentage and the second number drawn represents the second digit of the percentage.

For example, if a 6 and a 4 are drawn, take the acceptance sample from the truck that contains the cubic yard which represents the sixty-fourth percentile of the sublot; that is, if the sublot size is 50 $yd.^3$, take the sample from the truck containing the thirty-second cubic yard. If the sublot size is 100 $yd.^3$, take the sample from the truck containing the sixty-fourth cubic yard of the sublot.

At the end of a job where a full sublot will not be placed, compute the percentage of the sublot in the usual manner. If the percentage determined by the random drawings exceeds the amount of concrete to be placed, do not sample. If it is within the amount to be placed, treat as an additional sublot and make the usual tests.

Example: The random digits drawn are 5 and 4. Thus, the percentage is 54. If the last sublot to be placed represents more than 54 percent of the usual sublot size, take the acceptance sample from the truck containing the fifty-fourth percentile. If less than 54 percent of the normal sublot is to be placed, do not sample.

The truck load to be sampled for each sublot should be established prior to beginning the concrete placement. However, this information should be kept confidential until the load to be sampled arrives on the job.

While the particular randomizing method to use is a matter of convenience or judgement, it is emphasized that arbitrarily selecting a load for sampling other than the one selected by the randomizing procedure must not be permitted. Only when a load designated as an acceptance sample is rejected and removed from the job should a change be made. In this case the next load placed automatically becomes the load for acceptance sampling.

START-UP AND MONITORING PROCEDURES

Start-up procedures and requirements concerning proper moisture determinations in the aggregate, mixing temperatures, etc., remain unchanged. Although under both the old and revised specifications it is the contractor's responsibility to control all the properties of the concrete within the specification limits, monitoring of air content by state personnel at the beginning of a placement is desirable. The state's final acceptance for air content, however, is to be based on the statistical analysis of the test results on the randomly selected acceptance samples.

A special procedure has been introduced for monitoring the air content of bridge deck concrete. Under the new procedure, at the beginning of each day, when 3 consecutive loads of concrete show that the amount of entrained air is within the required specification limits and the average of the three tests is within ± 0.8% of the target value (mid-point of range for air), reduced monitoring can be instituted on the basis of 1 randomly selected sample for each 5 loads.

Monitoring tests may be made using the Chace air indicator. However, a determination must be made by the air pressure meter or the volumetric method before a load of concrete is rejected. Any load for which the air content determined by the last two procedures is outside the specification limits should be rejected and removed from the job. When this occurs for a load that would normally be sampled for acceptance tests, all data and specimens, if already made, will be discarded, and the next load to be placed in the job will be so sampled. This is consistent with the randomizing procedure, since the characteristics of the concrete placed in the structure and not the concrete produced are desired.

ADDITIONAL TESTS REQUIRED FOR SIMULATED APPLICATION OF REVISED SPECIFICATION

Acceptance for strength under the new specification is to be based on 28-day tests on the randomly selected acceptance samples required for the revised specification. These can also be used as the acceptance tests for the present specification. However, if the usual 14-day breaks as well as the 28-day breaks are desired, make 2 sets of 3 each of 4 in. x 8 in. cylinders for the projects selected for the simulated application of the revised specification. Test one set at 14 days and the other at 28 days. The additional data for small cylinders at 14 days may permit subsequent revision of the specification to permit statistical acceptance on the basis of 14-day tests. A test for entrained air by the air pressure meter must be made for each acceptance sample.

DATA REPORTING

Field personnel will continue to record all data on the same forms as in the past and send in reports to the Materials Division, except that the reports for the simulated projects should so indicate. These data will be used to compute acceptance and simulated pay factors. For any placements in which the amount of retarders, water-reducing agents, or water have been intentionally varied, the records submitted should also so indicate.

PAY FACTORS

Recent analyses of the statistical significance of the criterion for acceptance, and for computing pay factors, have raised some doubts that the producer's correction as now provided for in the proposed revision is valid in all cases and further study is needed. However, the data needed would not be affected by any changes in the manner of computing pay factors. Thus, for the time being, field personnel need not estimate simulated pay factors.

APPENDIX C

PROPOSED REVISION TO VIRGINIA DEPARTMENT OF HIGHWAYS AND TRANSPORTATION SPECIFICATIONS FOR HYDRAULIC CEMENT CONCRETE

"Road and Bridge Specifications"
July 1, 1982

Section 219

NOTE: Subsections reproduced in small type are unchanged from present specifications except for numbering.

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. The Contractor will be permitted to produce Class A3 General Use cement concrete for incidental construction items from a mobile production plant. Unless otherwise specified, mobile production plants will not be permitted for the production of concrete used in bridge, box culvert, pavement, or retaining wall construction.

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. Type I, Type II or Type III cement may be used in latex portland cement concrete.

(b) **Formulated** latex modifier shall be a non-toxic, film forming, polymeric emulsion to which all stabilizers have been added at the point of manufacture and shall be homogenous, uniform in composition and free from chlorides.

The latex modifier shall conform to the following requirements:

Polymer Type	Styrene Butadiene 68 ±4% Styrene 32 ±4% Butadiene
Average Polymer Particle Size	1500 to 2500 Angstroms
Emulsion Stabilizers . . .	Anionic and non-ionic surfactant
Percent Solids	46.5 to 49.0
Weight (lbs. at 25°C) per Gallon	8.40 to 8.55
pH	9 to 13
Shelf Life	2 Years
Color	White

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

(d) **Coarse aggregate** shall be stone, air-cooled blast furnace slag, or gravel conforming to Section 203 for the class of concrete being produced. Coarse aggregate for the deck surface concrete of two-stage bridge deck construction shall be non-polishing Size No. 7 or No. 8 conforming to Section 203.

(e) **Water** shall conform to Section 218.

(f) **Admixtures** shall conform to Section 217.

(g) **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 aggregate from taking place during handling or hauling. The inclusion of foreign materials, when the aggregates are being removed from the transporting vehicle 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.

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(b) **Cement:** Reclaimed cement or cement that shows evidences 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) **Latex Modifier:** Precautions shall be taken to protect latex modifier from extreme heat or cold. The stored latex modifier shall be kept in enclosures which will protect it from exposure to temperatures below 40°F or in excess of 85°F. Drums of latex modifier stored at bridge sites shall be protected from direct sunlight.

(d) **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. Except as specified hereinafter, 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.

When using mobile production plants aggregates, cement and water shall be measured by weight or volume. In the event ingredients are measured by volume, the Contractor shall furnish, at his expense, approved scales and containers suitable for checking the calibration of the equipment's measuring system. The manufacturer's recommendations shall be followed in the operation of the equipment and in calibrating the various gages and gate openings. Mixing water shall be measured by means of a calibrated flow meter. The introduction of mixing water to the mixer shall be properly coordinated with the introduction of cement and aggregates. Ingredients shall be proportioned within the following tolerances which are based on the volume-weight relationship established by calibration of the measuring devices:

Cement	0 to +4%
Fine Aggregate	±2%
Coarse Aggregate	±2%
Admixtures	±3%
Water	±1%

A means shall be provided whereby samples of the various ingredients can be taken from the feed prior to blending and mixing to check the calibration of the equipment.

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 plant 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 inticate 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 as 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.

(e) **Mobile Production Plants:**

In the event the Contractor elects to utilize a mobile production plant as permitted in Section 219.01, the equipment requirements specified hereinbefore will not apply and the concrete shall be mixed at the point of delivery by a combination materials transport and mixer unit conforming to the following:

The unit shall be capable of carrying, in separate compartments, all the necessary ingredients needed for concrete production and be capable of mixing the ingredients at the point of delivery. The unit shall be equipped with calibrated proportioning devices to vary mix proportions of dry ingredients and water. The unit shall be capable of changing the slump at any interval of continuous discharge of concrete.

The mixing mechanism shall be a part of the transportation unit carrying the dry ingredients. The mixer may be the auger type or any other type 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.

Each unit shall have attached thereto, in a prominent place by the manufacturer, a metal plate or plates on which is plainly marked the gross volume of the transportation unit in terms of mixed concrete, discharge speed and the weight-calibrated-constant of the machine in terms of an indicator revolution counter. The mixer shall produce, within the specified time of mixing, a thoroughly and uniform concrete, continuously discharged with a satisfactory degree of uniformity.

During discharge, the consistency, determined by the slump cone method on representative samples taken from the discharge of the mixer at random intervals, shall not vary by more than one inch.

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 the 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 termporarily 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 Inspection will never assume by act or word the responsibility of batch control adjustments, calculations, or the setting up dials, gages, scales and meters.

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 termporarily 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 Inspection will never assume by act or word the responsibility of batch control adjustments, calculations, or the setting up 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, or shall have his source of supply 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 finished 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 211.1). The actual quantities used, as determined by the methods described herein, shall not deviate more than plus or minus 5 percent from such quantities.

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:

Use an approved water reducing admixture;
Increase the cement content;
Change the source of coarse aggregate;
In hot weather, add ice or otherwise reduce the temperature to increase the workability;
other recommendation by the Contractor as approved by the Engineer; however,

when any of the options are exercised, the Contractor shall make trial batches under the observation of the Engineer to verify that the concrete of the required workability and consistency is within the maximum water content. At least one trial batch shall be made with the concrete temperature at approximately 90°F to verify that the concrete mix has sufficient workability and consistency without exceeding 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. All costs incurred due to adjustments of concrete mix design(s) and for trial batches shall be borne by the Contractor and no additional compensation will be made.

Air and consistency checks will be performed by the Department to insure that the specification requirements are consistently being met for each class of concrete prior to discharge into the forms. The sample secured for the tests is to be taken after not less than 2 cubic feet has been discharged into a suitable container other than the forms. Should either determination yield a result which is outside the allowable range of air content or consistency, the following procedures will be taken:

(a) The Inspector will immediately perform a recheck determination and should the results confirm the original test, the load will be rejected.

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

(c) The Contractor's representative shall be responsible for notifying the producer of the test results through a preestablished means of communication.

Nothing herein shall be construed to preclude the Engineer from taking any additional tests deemed necessary, and rejecting remaining material which fails such tests.

The adding of cement to those loads previously rejected for excessive water content or consistency will not be permitted.

TABLE II-15

REQUIREMENTS FOR HYDRAULIC 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***	5,000	57	1 in.	A	635	0.49	0 - 4	0 - 2	4±2
A4 Posts and rails**	4,500	7	½ in.	A	635	0.45	2 - 5	1 - 3	7±2
A4 General Use	4,500	57	1 in.	A	635	0.45	2 - 4	0 - 2	6½±1½
A3 General Use	3,000	57	1 in.	A	588	0.49	1 - 5	0 - 3	6±2
A3 Paving	3,000	57	1 in.	A	564	0.49	0 - 3	0 - 2	6±2
B2 Massive or lightly reinforced	2,200	57	1 in.	B	494	0.58	0 - 4	0 - 2	4±2
C1 Massive unreinforced	1,500	57	1 in.	B	423	0.71	0 - 3	0 - 2	4±2
T3 Tremie Seal	3,000	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.

*For acceptable concrete the average strength test results shall exceed this minimum by a sufficient amount so that, based on statistical principles and assuming normal distribution, not more than 10 percent of the population of strength results will be below the indicated value. Typically, the mix design utilized is expected to provide average test results at least 750-1000 psi higher than the design minimum laboratory compressive strength at 28 days.

**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.

***When Class A5 concrete is used as the finished bridge deck riding surface, or when it is to be covered with bituminous concrete with or without Class 1 waterproofing, the air content shall be 6 1/2 ± 1 1/2 percent.

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

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 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 weigh 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 designated 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 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) **Automatic Mobile Continuous Mixers:** Mobile continuous mixers shall be calibrated to accurately proportion the mix design and shall have been certified within 60 days prior to use on the project for the specific type of material. Certifications will be valid for a maximum period of 6 months or until the source of materials changes or the gradation or moisture changes significantly to affect the consistency of the concrete.

Evaluation and certification will be performed by the Department or an approved testing agency to determine that the true yield is within a tolerance of ±1.0 percent. A recording meter, visible at all times and equipped with a ticket print-out, shall indicate calibrated measurement.

(d) **Hand Mixing:** Except as otherwise specified, hand mixing will only be permitted in case of emergency and with special permission. When permitted, the batches shall not exceed ½ cubic yard and shall be mixed in a watertight container in a manner approved by the Engineer. The component materials shall be measured by placing them in any suitable, rigid container in the volumetric proportions of 1:2:2½, cement to fine aggregate to coarse aggregate. The container shall be filled and leveled with each component ingredient to insure the proportions specified as near as possible. Water shall be added to produce a slump not to exceed 3 inches.

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 method 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 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 Type II 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 through 219.19, except that, where applicable, compressive strengths at 7 days shall be used in lieu of compressive strengths at 28 days.

Sec. 219.11 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 testing reports.

Sec. 219.12 Acceptance of Concrete —

(a) The Department shall be responsible for all sampling and testing for acceptance of all concrete. The procedures used and criteria applied will vary depending on the class of concrete and the purpose for which it is used.

1. Pavement, structural, bridge deck, and incidental concrete.

   Acceptance of these classes of concrete shall be on a lot-by-lot basis using the procedures and criteria described in Sections 219.13 through

219.18. The requirements of Section 321.22 also apply to pavement concrete.

2. Prestressed concrete shall be accepted as described in Section 219.20.

3. Lean cement concrete shall be accepted as described in Section 219.21.

(b) In addition to the prescribed procedures, the Department may reject any concrete which is obviously defective, or test any concrete and reject that which does not meet the requirement of these specifications.

Concrete which fails to meet all acceptance criteria 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).

Sec. 219.13 Acceptance of bridge deck, structural, incidental, and pavement concrete. — These types and classes of concrete shall be accepted on a lot-by-lot basis as defined below.

(a) Definition of a Lot: A lot is defined as a definite quantity of concrete manufactured under conditions of production that are considered to be uniform and where the source of all major ingredients (coarse aggregate, fine aggregate and cement) are the same. The quantities to be considered a lot for different construction activities are as follows:

1. Bridge Deck Concrete — The concrete placed as a deck shall normally be considered a lot. However, if the volume of concrete in the deck exceeds 1,000 cubic yards, multiple lots, each consisting of approximately 500 cubic yards, shall be established. All the concrete in one day's production shall be included in the same lot. When a producer places more than one bridge deck in a day, and the concrete in all the decks is made from the same source of materials and with the same mix design, the total concrete in all the bridge decks so placed may be considered as one lot and random sampling of sublots shall be conducted as in 219.13(C)-1, except that at least one sample shall be randomly selected from each bridge deck within the lot and tested in accordance with these specifications.

2. Structural and Incidental Concrete — Unless otherwise stated, all such concrete of a given class included as a separate bid item in a contract will be considered a single lot. For contracts extending over a long period of time, the Engineer shall decide if it is advantageous to treat different portions of the contract as separate lots. The Contractor shall be informed of such decisions prior to placement of the concrete.

3. Pavement Concrete — The nominal lot size for pavement concrete will be 1,000 cubic yards. Paving contracts involving less than 1,000 cubic yards shall be considered a single lot. Partial amounts at the end of a contract shall be considered a separate lot if the amount exceeds 300 cubic yards. Amounts less than 300 cubic yards shall be considered a part of the previous lot.

(b) Inspection and Testing

1. Temperature: The Contractor is responsible for furnishing concrete within the temperature ranges established in Section 219.10. However, when considered necessary, 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 219.10 will be rejected and removed from the job.

2. 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.

3. Tests for Air Content, Consistency, and Strength: Sampling and testing for air content, consistency, and strength shall be conducted in accordance with Sections 219.14 and 219.15.

4. When at any time, the Department's representative observes placement or construction practices not in accordance with the requirements of Section 219, (for example, delay in placing curing compounds, inadequate vibration, improper finishing, or manipulations and delays that could result in abnormal

loss of entrained air), he shall note such observed deficiences on Form TL-28 and shall immediately notify the Contractor's representative of his action and the notation made. In these cases, the State reserves the right to make additional inspection and tests on the hardened concrete, and when deemed desirable shall base the acceptance for strength of the concrete on the results of cores taken, tested, and evaluated for strength as described in Section 219.15(a)3. Where loss of entrained air is suspected, acceptance for air content shall be based on the characteristics of the air void system as described in Section 219.16(c).

When poor practices or curing deficiencies have been noted by the inspector, the decision as to whether to use cores for acceptance of strength and hardened concrete tests for acceptance of air entrainment shall be made by the Engineer. Should such coring and tests for entrained air result in a full pay factor of 1.0, the costs of the coring and additional testing shall be paid by the state. If a reduction in pay factor results, the costs of the coring and the additional tests shall be paid by the contractor.

Sec. 219.14 Sampling and Testing —

(a) Initial and Monitoring Sampling and Testing: The first batch during each production day shall be sampled and tested for air content, slump, and, when deemed desirable, temperature 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, temperature, 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 cubic feet have been discharged. Initial and monitoring air content tests may be performed by AASHTO T-152 (air pressure meter) T-196 (volumetric method) or T-199 (Chace air indicator). When T-199 is used the average of at least two determinations shall be considered a test. 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 the test results through a preestablished means of communication. If the recheck test shows compliance with the specifications, 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 described in VTM-XX. The portion secured for each test is to be taken after not less than 2 cubic feet 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 paragraph (c).

(c) Frequency of Acceptance Sampling:

1. Bridge decks — Select one sample randomly for each sublot of 50 cubic yards. For a partial sublot at the completion of a deck, determine the portion of the sublot to be sampled in the usual manner. If the volume of concrete to be placed exceeds the designated cubic yard, sample and test in the usual manner as a full sublot. If

the volume of concrete to be placed is less than the designated cubic yard, do not sample that portion of the concrete. When more than one bridge deck is to be considered a lot as defined in Section 219.12(a)1 and the normal randomizing procedure does not designate a portion of concrete to be sampled from any bridge deck, select a sample from that deck by using the random procedure to determine the portion of the concrete in that deck to be sampled. If a single small bridge deck constitutes the total concrete in a lot, a minimum of 2 randomly chosen samples shall be taken.

2. Structural Concrete (bridge members [except decks] box culverts, retaining walls, and miscellaneous) — Select 1 sample from each sublot of 100 cubic yards. For small structures involving lot sizes greater than 50 cubic yards but less than 200 cubic yards select a minimum of two samples by using the randomizing procedure to determine the portions of the lot to be sampled. When the volume of concrete in the lot is less than 50 cubic yards,sampling and testing may be waived and the concrete accepted by visual inspection.

For portions of sublots less than 100 cubic yards at the end of a placement to be considered a lot, select the cubic yard of concrete to be sampled by the usual randomizing procedure for a sublot. If the volume of concrete to be placed exceeds the designated cubic yard, sample and test in the usual manner as a full sublot. If the volume of concrete to be placed is less than the designated cubic yard, do not sample.

(d) Initial Acceptance Procedure for Air Content and Slump of Bridge Deck Concrete: At the start of concrete production for a bridge deck, every batch shall be sampled and tested (100 percent sampling and testing) for air content and slump as described in 219.13(a). 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 percent sampling and testing when the test results for three successive batches are within the specification limitations for air content and slump. However, 100 percent 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 structural and incidental concrete shall be in accordance with Sections 219.15 through 219.18. The requirements of these sections also apply to pavement concrete, in addition to the requirements in Section 321.22.

Sec. 219.15 Acceptance Criteria for Compressive Strength — 28-day compressive strength tests will be made in accordance with AASHTO T22, T23, and/or T24, except that the Department reserves the right to modify the testing of specimens to allow the use of elastomeric caps in lieu of the specified capping materials. Acceptance criteria for compressive strength will vary depending on the number of samples (n) tested for the lot as follows:

(a) When the number of samples is equal to or less than 5.

1. Accept at bid price when the average of valid compressive strength results at 28 days is equal to or greater than 750 pounds per square inch above the minimum design strength (f'_c) given in Table II-15 of Section 219 for the class of concrete involved and no valid test result is more than 500 pounds per square inch below f'_c. A valid test result is defined as the average of 3 test cylinders made from the same batch of concrete. However, the average of results on 2 cylinders from the batch may be considered a valid test result if they agree within 10 percent of their average and the third cylinder is obviously defective.

2. Accept at a reduced pay factor when the average of valid compressive strength results at 28 days is between 749 and 148 pounds per square inch above f'_c. The pay factor for strength will be determined by the following equation:

$$PFS = (QL + 10)/100,$$

where

PFS is the pay factor for strength,

QL is the percent within specification limits for strength based on the value of the quality index, Q, and is determined from the normal distribution curve(assuming that Q = z and that the standard deviation is 586 pounds per square inch), and

Q is calculated as

$$Q = (\overline{X} - f'_c)/586.$$

3. When the average 28-day strength of the concrete is less than 148 pounds per square inch above f'_c or a valid test result is more than 500 pounds per square inch below f'_c, an investigation will be made to determine the cause of low strengths. Five cores shall be taken from noncritical portions of the structure. If the average strength of the cores is more than 148 pounds per square inch higher than $f'_c \times 0.85$ and no core has a strength less than 500 pounds per square inch below $f'_c \times 0.85$, the concrete will be left in place and paid for on the basis of the strength of the cores. The pay factor for the core strengths shall be determined by establishing the QL on the basis of an adjusted strength equal to

$$\bar{X}\text{ (adjusted)} = \bar{X}\text{ (cores)}/0.85.$$

(b) When the number of samples in the lot is more than 5 and a pooled standard deviation as described in paragraph c is not available.

1. Accept at full bid price when

$$\bar{X} \geq f'_c + 1.28\ s,$$

where

$\bar{X}$ is the average strength at 28 days,

f'_c is the minimum design strength at 28 days,

s is the standard deviation of the sample, except that the minimum value used in computation shall be 400 pounds per square inch and the maximum value shall be 800 pounds per square inch.

2. Accept at a reduced price when the average is between $f'_c + 1.28\ s$ and $f'_c + 0.253\ s$. The pay factor for strength shall be computed as:

$$PFS = (QL_s + 10)/100,$$

where

PFS = Pay factor for strength, and

QL is the percent within specification limits for strength based on the value of the quality index, Q, and is determined from the normal distribution curve assuming that Q = z and using the sample standard deviation, except that the minimum standard deviation used in the computation shall be 400 pounds per square inch and the maximum standard deviation shall be 800 pounds per square inch.

$$Q = (\overline{X} - f'_c)/s.$$

3. When the average 28-day strength of the concrete is less than $f'_c + 0.253\ s$ or a valid test result is more than 500 pounds per square inch below f'_c, an investigation will be made to determine the cause of low strengths. The investigation and acceptance procedures shall be as described in Section 219.15(a)3.

(c) When a concrete producer has established a standard deviation for his production by 30 or more certified strength tests on the same class of concrete using the same mix design within a period of 90 days, the standard deviation shall be computed on the basis of the most recent 30 tests. When previous production is included to establish the standard deviation, all strength tests made on the lot plus the results of an additional number of the most recent tests to bring the total number of samples to 30 shall be used. Acceptance and pay factors for strength shall be computed as in 219.15(b).

Sec. 219.16 Acceptance Criteria for Entrained Air Content — At the time of placement, concrete will be accepted or rejected for air content on the basis of monitoring and/or acceptance samples as described in Section 219.13. Such acceptance or rejection is based on individual samples being within the minimum and maximum range established for the class of concrete in Table II-15. However, it is also required that the average of all tests for entrained air in A3 and A4 concrete be above the following minimum limits:

A3 concrete, general use:	5.5 percent
A4 concrete, posts and rails:	6.0 percent
A4 General use, bridge decks:	6.0 percent

When the average of tests for entrained air is below the minimum specified but within 1.00 percentage point of that minimum, the concrete will be accepted at a reduced pay factor.

The minimum pay factor for air shall be 0.70 for concrete with the average air content 1.00 percent below the required minimum as given above. The actual pay factor for air shall be computed by the equation

$$PFA = 0.70 + 0.30\ [\overline{X} - (\overline{X}_{min.} - 1.0)],$$

where

PFA = pay factor for air,

$\overline{X}$ = average of test results on acceptance samples, and

$\overline{X}_{min.}$ = minimum acceptable average for class of concrete involved.

For the purposes of this computation air contents shall be calculated to 2 decimal places.

Should the average air content be more than 1.00 percent below the specified minimum, an investigation of the air void system of the hardened concrete shall be made. If microscopical examination shows that the spacing factor, $\overline{L}$, computed by ASTM Method C457, is 0.008 inch^{-1} or less, the concrete will be allowed to remain in place and a reduced pay factor for air of 0.70 shall be applied.

Sec. 219.17 Combined Pay Factor by Acceptance — In the event that the pay factor for both air content and 28-day strength are less than 1.0, a net reduced pay factor will be computed as

$$PFN = PFA \times PFS.$$

The minimum value of PFN to be used in the computations for Section 219.17 will be 0.50.

PFN for large projects will be projected periodically during the course of production on the basis of completed tests. In the event that PFN is less than 1.00, progress payments will be reduced accordingly.

If at any time during production either PFA or PFS 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 Engineer will order production ceased until the deficiencies are effectively corrected.

Sec. 219.18 Basis of Payment — If the concrete is subject to a price reduction, the following procedures will apply.

(a) For concrete bid by the unit (cubic yard, etc.)

PR = Q x BP x (1-PFN),

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

PFN = net reduced pay factor.

(b) For concrete included in a lump sum

PR = Q/T x LS x (1-PFN),

where

T = total quantity of concrete in the item,

LS = lump sum bid price, and

other symbols are the same as in (a).

Sec. 219.19 Pay Factors for Pavement Concrete — All appropriate requirements for materials used, proportioning and mixing concrete quality control, and acceptance procedure as previously defined in Section 219 shall apply. In addition, a reduction in pay for insufficient thickness as described in Section 321 as indicated, the final pay factor for the concrete shall be the product of the indicated pay factors. That is,

PFN = PFCQ x PFCT,

where

PFN = final pay factor,

PFCQ = pay factor for concrete quality, and

PFCT = pay factor for concrete thickness.

Sec. 219.20 Pretensioned Prestressed Concrete, Class A5 — The concrete used in the manufacture of prestressed concrete structural members shall be composed of materials meeting the previous requirements of this section, with the following modifications:

(a) **Design and Proportioning of Mix:** The concrete mix proportions shall be such that the minimum compressive strength of cylinders made and tested in accordance with AASHTO T22 and T126 shall be 3600 psi at 7 days and 5000 psi at 28 days.

(b) **Control Tests:** The concrete shall have attained a minimum compressive cylinder strength of 3500 psi for piles and 4000 psi for other members before the tension in the strands is released and the stress transferred to the concrete, unless otherwise specified. Except for normal removal from the stressing bed to the storage area, the concrete shall have attained a minimum compressive cylinder strength of 5000 psi before the structural members may be handled.

During each concreting operation, a minimum of 6 cylinders will be made and shall be cured under the same conditions as the concrete deck members or piles. These cylinders will be tested in accordance with AASHTO T22 to determine the time at which the stress may be released, and the time at which the structural members may be handled or transported other than normal removal from the stressing bed, as specified hereinbefore.

During concreting operations at plants where steam curing of prestressed concrete members is used, the Engineer will make, for the verification of the quality of the design mix, from the same batch of concrete, 3 cylinders for each placement unless, previous experience indicates that control cylinders are not necessary.

The Engineer will make frequent observations of the consistency of the freshly mixed concrete. The Contractor shall provide the labor necessary for and the means of obtaining the samples of concrete.

The Contractor shall furnish cylinder molds conforming to AASHTO M205 for all test specimens.

(c) **Requirements for Plant Approval:** All installations (temporary or permanent) for the manufacturer of precast, prestressed bridge elements which have not previously produced elements for the Department, will be inspected and must be approved by the Engineer prior to the commencement of work.

Request for plant inspection shall be made by the Contractor to the Engineer at least 3 weeks prior to the date of inspection. Before the plant inspection is made, a preliminary conference will be held on a date and at a place designated by the Engineer, to discuss in detail the plant facilities, materials, and the production methods the Contractor intends to use. This conference is to be attended by a responsible representative of the Contractor.

In the event an installation has been producing prestressed elements for the Department on a continuing basis, plant inspection will be performed annually. However, the Department reserves the right to perform inspection at any time deemed necessary by the Engineer.

In order to fully qualify installations for the manufacturers of members other than piling, the Department reserves the right to require the Contractor to test a member which is representative of each different design type (I-beam, box, slab, etc.) and size of cross-section of the members to be manufactured, and the acceptance test shall be as follows:

Acceptance Test: Not more than one line of members shall be cast prior to the satisfactory completion of the acceptance test. A representative member shall be tested in accordance with VTM-20 in the presence of the Engineer prior to plant approval.

If the recovery of the member, on removal of the final load, is more than 90 percent as determined by VTM-20, it will be considered acceptable. If any cracks appear at any time during the test, the tested member, and other members already manufactured, shall not be incorporated in a structure until the Engineer has determined that such cracks are not detrimental to the satisfactory performance of the structure and until he has reviewed and approved any necessary modifications of the method of manufacture.

The member to be tested will be selected at random by the Engineer. The jigs and load testing equipment shall be subject to approval. The cost of the member selected for test, or of any other member which may require testing, together with the cost of the test, shall be borne by the Contractor.

The Contractor shall submit to the Engineer, 2 weeks prior to the preliminary conference, complete plans and computations for the installation whereon it is proposed to cast and stress the bridge elements and the method he proposes to use in testing the bridge members. The plans shall indicate the maximum safe capacity of the installation. Such plans shall be prepared by a qualified engineer, experienced in pretensioned plant work.

The bed and buttresses shall be pretested to a load equal to 120 percent of that load required for the production of that member having the maximum strand group and highest center of gravity for which the bed is to be used. Test loads shall be applied and maintained for 24 hours before any part of the full load is reduced.

The Contractor shall certify that he has engaged the services of a qualified engineer for the supervision of the construction of the installation as well as for the early production stages of the products to be cast.

The Contractor shall submit detailed data of the procedure he proposes to follow in pretensioning and stress release, as well as all details relating to the proposed stressing and handling equipment. The Contractor shall submit to the Engineer all plans, shop drawings, details, and beam test computations at least 2 weeks prior to the expected time of the particular plant operation. The Contractor may authorize, in writing, the fabricator to act for him in matters relating to working drawings, as indicated in Section 105.02.

All prestressing plant facilities and plant operation procedures shall be subject to approval by the Engineer, including, but not necessarily limited to the following:

1. Foundations and casting slabs.

2. Strand anchoring, tensioning units, and tension release devices, including accurate stress indicating gages or devices.

3. Anchoring and tensioning units equipped with satisfactory spacing devices to insure accurate location of strands in the prestressed member.

4. Method for attaining and maintaining design stresses in individual strands until stress transfer.

5. For long casting beds, spacers or supports for maintaining the strands at their proper elevation in the member.

6. Gages meeting the requirements of Section 405 or other devices to insure uniform initial stress in all the strands included in each group prior to the application of the design prestress force.

7. Equipment for molding concrete cylinders. Equipment for testing the cylinders, if furnished by the Contractor, shall conform to the requirements of ASTM E4.

8. Enclosures, covers and equipment to effect the proper curing of the concrete in all types of weather and under all conditions.

9. Steam curing equipment.

10. Adequate facilities and space for the proper protection, storage and handling of all materials and structural members.

11. Separate storage for cement.

12. Facilities for proportioning and mixing concrete.

13. The concrete mix design shall be submitted to the Engineer 2 weeks prior to the plant inspection.

14. Vibrating equipment including at least 2 spare vibrators in operative condition.

15. Suitable shelter for the use of the Engineer and Inspectors in making reports, checking drawings and specifications, conducting tests of materials and for storage of field equipment, test apparatus and records.

16. Necessary provisions for plant erection of bridge beams for checking bearings.

17. Handling equipment and procedure and the condition of the haul road over which prestressed members are to be moved from the beds to temporary storage.

Approval of the requirements herein will not relieve the Contractor of the responsibility for the satisfactory performance of his methods, procedures and equipment.

Sec. 219.21 Lean Cement Concrete shall conform to the requirements for hydraulic cement concrete with the following modifications:

Cement shall be Type I, Type I-P or Type II conforming to Section 216.

Aggregates shall be Aggregate Base Material, Type I No. 21A consisting of crushed stone or crushed gravel conforming to Section 209 except the mixing requirements of Section 209.05 will not apply.

The design and proportioning of the cement and water shall be based on the dry weight of the No. 21A aggregate. The minimum cement content shall be 7% by weight and the water content shall not exceed 15% by weight unless otherwise approved. The concrete mix proportions shall be such that the minimum compressive strength shall be 500 psi at 7 days, as verified by cylinders made and tested in accordance with AASHTO T22 and T126.

An approved water reducing admixture shall be used in accordance with the manufacturer's recommendations, or as approved by the Engineer.

The air content of the concrete mixture shall be 4% with an acceptance tolerance of ±2% when tested in accordance with AASHTO T152 or T196.

The consistency of the lean cement concrete shall be uniform and shall have a slump of not more than 4 inches.

The Contractor shall, at his own expense, prepare trial batch concrete test specimens based on the proposed mix designs. The results of said tests shall be submitted to the Engineer for review.

The Contractor shall submit, for review and acceptance, concrete mix design(s) meeting the aforementioned requirements.

Mixing shall be performed at the job site in an approved central mix plant, except that transit mix may be furnished for use in miscellaneous lean cement concrete base such as transitions, connections and crossovers.

APPENDIX D

Modifications required in Chapter 4, Portland Cement Concrete of the Manual of Instructions, Materials Division, Virginia Department of Highways & Transportation to establish compatibility with revisions in Section 219 of Road and Bridge Specifications, Virginia Department of Highways and Transportation.

(Revisions to be made in Sections 411, 412, 415, and 416)

SECTION 411 STRUCTURAL AND MISCELLANEOUS CONCRETE

Sec. 411.01 GENERAL—In order to insure quality control as well as to determine various strengths of concrete, structural and miscellaneous fresh concrete is sampled in the field for compressive strength tests, in addition to air content, consistency, and other tests. Structural concrete is considered to be bridges, box culverts, and retaining walls, while miscellaneous concrete includes all concrete except pavement, prestressed, and structural.

On concrete structures, the concrete is not in flexure as a beam, but in compression; hence, the need for determining the compressive strength. The batches of concrete to be sampled and tested for acceptance are to be chosen by a randomized procedure. The selection of the batches is made at the beginning of the job, in accordance with VTM XX.* The loads or batches to be sampled are not revealed to the Contractor until the materials arrive on the job. Section 219 of the specifications has requirements for strengths based on statistical concepts. Thus, for non-biased results, random sampling must be adhered to. The sampling shall be conducted only by properly authorized and trained personnel. The necessity of properly preparing and caring for compressive strength test specimens must be stressed to the personnel involved. Concrete cylinders cast on the job are used for purposes of compressive strength tests, which are a major basis of acceptance of the concrete and the level of strength could affect the amount of payment received by the Contractor.

Sec. 411.02 COMPRESSIVE STRENGTH SPECIMENS—

(a) General—Compressive strength specimens are to be made by casting fresh concrete in cylindrical steel molds. Records shall be kept of all tests of concrete mixes, in accordance with Paragraph (f) below.

(b) Sampling — Concrete for the test specimens shall be taken from the selected batches immediately before they are placed in the work, in accordance with AASHO Specification, Designation: T 141, or as modified herein. The member or section of the structure into which the concrete has been placed shall be noted clearly for future reference. THE SAMPLE OF CONCRETE FROM WHICH TEST SPECIMENS ARE MADE SHALL BE REPRESENTATIVE OF THE ENTIRE BATCH.

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*The proper test number is to be determined.

An air content and a consistency test, as outlined in Sections 409 and 408 respectively, shall be made of the same batch of concrete from which the cylinder is cast, and the data recorded as for the other tests, with an identification number of description added.

(c) Molding and Curing—Molding and curing of the cylinder specimens shall be accomplished, as outlined in AASHO Specification, Designation: T 23, or as modified herein. Molds should not be left out in the hot sun before casting the specimens. Single-use molds will not be permitted.

Molds shall be placed on a rigid horizontal surface free from vibration and other disturbances. After the casting of the cylinders and during the first 24 hours, all test specimens shall be stored under conditions that maintain the temperature immediately adjacent to the specimens in the range of 60° to 80° F. and prevent loss of moisture from the specimens. Wet burlap (or damp sponge from shipping can) shall be placed over the specimens to maintain the temperature and to prevent loss of moisture. After the burlap has been moistened and placed over the cylinders, moisture proof material (such as polyethylene or plastic) shall be placed over the cylinders. Care shall be taken to see that this is sealed by use of a string, rubber band, or other device. The cylinders shall be protected from heat and cold during the entire field storage period.

Cylinders used for *quality (acceptance)* shall be removed from the molds at the end of the first 24 hours and placed in the shipping cans that contain sponges that are moist. Do not leave an excess amount of water in the shipping cans. The sponges may be moistened by putting water into the can and then draining off the excess water after the sponges become completely moist. The quality specimens shall be submitted to the Laboratory as soon as possible after the molds are removed. It is important that these cylinders be placed in the temperature-humidity controlled room when the cylinders are at a very early age.

Cylinders used for *early form removal (control specimens)* shall be removed from the molds at the end of 24 hours and placed adjacent to or near the concrete structure. These cylinders shall be cured at the same temperature and moisture condition as the structure. These specimens shall be submitted to the Laboratory for test on the day prior to the desired testing date. *Do not send the cylinder several days prior to the specified testing date.* The Laboratory has no way of duplicating the same cure as that being applied to the structure. If these cylinders are tested on portable compression testing machines, see further details in Sections 401.01 (b) and 411.02 (e) herein. .

(d) Frequency of Sampling — The required minimum frequency of sampling is stated in Section 219.14(c). This varies with the type of structure in which the concrete is being placed. For bridge decks, 1 random sample is required for each 50 cubic yards in the deck. Generally, if the volume of the concrete exceeds 150 cubic yards, and is less than 500 cubic yards, each bridge deck should be considered a lot. For small jobs when more than one deck is being placed under the same contract with concrete from the same mixing plant at approximately the same time, the concrete for all such decks may be considered a single lot, and randomized samples taken on the basis of all the concrete produced for the contract. However, under these circumstances random procedures must be applied so as to assure that at least one sample is taken from each deck so placed. For large decks exceeding 1,000 cubic yards, multiple lots each consisting of about 500 cubic yards should be established.

For other structural concrete, one set of 3 cylinders shall be made for each 100 cubic yards of concrete placed. There is a minimum of 2 sets of 3 cylinders each per structure per class of concrete. The 3 cylinders in a set are to be made from the same batch of concrete. Under present specifications, all final acceptance tests are based on the 28-day compressive strength. However, where early information on the acceptability of the concrete is needed, additional sets of cylinders may be cast for testing at 7 or 14 days. On exceptionally large structures involving an unusually large amount of concrete or for miscellaneous concrete, permission may be granted by the State Materials Engineer, upon written request, to reduce the number of cylinders required per structure. In the case of projects containing less than 50 cubic yards of miscellaneous concrete, the District Materials Engineer may waive the requirement for compressive specimens, provided that this is documented in project records. Cylinder tests for the same class of concrete for other projects being supplied on the same day from the same plant may also be used to satisfy the testing requirement.

Concrete for rest area and landscape contracts will be tested the same as outlined above.

(e) *Testing*—Compressive strength specimens shall be prepared for testing in the Laboratory, in accordance with AASHTO Specification, Designation: T22, except that neoprene caps are used in lieu of the specified capping materials (see Section 219.15). herein. In the case of those cylinders tested on the portable compression testing machines, as outlined in Section 401.01 (b), it will not be necessary to cap these specimens in the normal manner. The use of cardboards furnished by the Department will be satsifactory in lieu of capping. The Inspector will operate this machine and record the test results in the project diary. No test report is written and no charges are made against the project other than the rental of the equipment, if it is State owned. The Inspector will also be responsible for transporting the control cylinders to the compression testing machine at the request of the contractor.

All specimens shall be tested at 28 days, except (1) when Type III or an increased amount of Type II cement is used, as outlined below, (2) when the specimen is used for a 14-day advance test, as outlined in Paragraph (d) above, and (3) when the specimen is used for early form removal or construction of superimposed elements, as outlined in Paragraph (c) above and in Section 401.01 (b).

When early testing at 14 days is conducted, strengths equal or greater than 85 percent of the design requirement shall be considered as indicative of concretes of suitable strength levels. However, final acceptance and computations of averages for pay factors shall be based on the 28-day tests.

If Type III cement is used, or an increased amount of Type II is used to obtain high early strength, these specimens will be tested at 7 days, and 100 percent of 28 day design strength must be obtained.

If low strength results are obtained at 7 days or at 14 days in either case above, or at 28 days if the specimen represents a cool weather back-up test or a progress record sample, there is a high probability that concrete with inadequate strength is being placed and steps are to be taken to discover and correct any conditions that may be responsible for low strengths.

District Laboratories will be permitted to test all of these cylinders, with the exception of 1 set of 3 cylinders from any one structure, which must be tested in the Central Office Laboratory.

(f) Acceptable Strength — Under the specification adopted in <u>(insert date of adoption)</u>, which introduced acceptance of concrete on the basis of statistical concepts, acceptable strength is defined in a different manner than before. In the revised specification both the average strength of the test specimens and the variability enter into a decision concerning the acceptability of the concrete. In addition, tests on each batch are not considered separately, but rather all the tests run on a <u>lot</u> (in many cases the concrete for an entire bridge deck, or all the concrete of a given class) are considered collectively as defining the characteristics of all the strengths in all the batches of concrete placed. For complete acceptance (100 percent pay factor) the specifications require that the test results indicate that not more than 10 percent of all of the strengths in the lot are below the minimum design strength, f'_c, of the class of concrete involved, assuming that normal distribution is present. This is often expressed as an acceptable quality level (AQL) of 90 percent or 90 percent within limits (PWL). The validity of this assumption has been established by a large amount of research. Research and experience have also shown that under this concept the strength result below f'_c would normally be scattered throughout the total concrete and, in effect, be surrounded by higher strength units so that overall the strength of the deck or structure would not be adversely affected (see ACI-214). It is emphasized, however, that this assumption is made on the basis of normal operations and procedures. If improper techniques are being used or obviously poor batches of concrete are being placed, deficiencies in the structure could result. Thus, it is important that the Inspector be alert for possible malfunctions of equipment or improper placement procedures.

It is also important to recognize that the average strength required for an AQL of 90 percent will vary depending on the variability of the strength test results as shown by the standard deviation, s. The required average is computed by the equation

$$\overline{X} = f'_c + 1.28\ s,$$

where

$\overline{X}$ is the required average,

f'_c is the minimum design strength,

s is the standard deviation, and

the factor 1.28 is derived from the normal distribution curve to determine the point for which 10 percent of the population will be below the designated f'_c.

As shown by the equation, the average required strength, $\overline{X}$, must exceed the minimum design strength by a varying amount depending on the standard deviation, and this amount increases as the standard deviation increases.

ACI 214, as well as other statistical sources, states that at least 30 tests are needed before it can be assumed that the standard deviation of a limited sample (number of test results) accurately indicates the standard deviation of the total population (all the possible samples). Using the recommended frequency of testing, most concrete projects placed by the Department do not require 30 determinations. Thus, for small jobs where 5 or fewer batches are tested, the specification makes provisions for assuming a standard deviation based on historical data and general knowledge of concrete technology. The assumed value is 586 pounds per square inch, which means that for all jobs requiring 5 or fewer tests, the acceptable average of test results for 100 percent pay is 750 pounds per square inch above the f'_c. That is, 3,750 pounds per square inch for A3 concrete, 4,750 pounds per square inch for A4 concrete and 5,250 pounds per square inch for bridge deck concrete.

For intermediate size jobs where more than 6 samples are tested and 30 results are not available from previous production by the same producer with the same mix design, the standard deviation of the sample itself is used for computing the required average for 100 percent pay factor, except that a minimum value of 400 pounds per square inch and a maximum value of 800 pounds per square inch are used. For large concrete producers and large jobs where 30 or more test results with the same mix design prepared within a 3-month period are available, the standard deviation of the last 30 results is used. This system gives a concrete producer with good quality control an advantage in that the required average for his product is lower than the required average for a producer with poor quality control.

The revised specification also recognizes that small deficiencies in the strength test results are not a sufficient basis for tearing out all the concrete. Thus, it establishes a system of reduced pay factors based on how much the strength is below the required amount.

Ideally, the deficiency in strength should be related to a deficiency in performance or durability, but this is not possible on the basis of present knowledge. Thus, the specification relates the reduction in payment to the Quality Level of the concrete as indicated by the average strength and standard deviation. The specification establishes a minimum pay factor of 0.70, which means that the minimum quality level for concrete to remain in place without coring and further investigation is 60 percent, since 100 percent pay is given for a 90 percent quality level. When the quality level is below 60 percent, tests must be made to determine the strength of the concrete in place and decisions made on the basis of such tests.

This system which spells out in advance the consequences of low strengths should avoid controversy over small deficiencies in strength. It should also tend to minimize such occurrences since the contractor knows he will be penalized for failing to produce concrete with the required strength.

(g) Acceptable Average Air Contents — The revised specification also includes a requirement for a minimum average air content in air entrained concrete. Monitoring requirements and determinations of air contents remain approximately the same, except for a randomized procedure for testing 1 in each group of 5 samples for bridge decks is established after the first 3 loads at the start of a day show compliance. However, a failure on the part of the concrete producer to consistently produce concrete near the center of the allowable range of air contents could result in a reduced pay factor. The reduction in pay occurs for low average air contents only. It is reasoned that any potential damage from a high air content would be a result of low strength, which is already subject to a reduction in pay factor.

(f) Reports—Field data for concrete cylinders will be reported on Forms TL-13 and TL-28 (ready-mix concrete), and laboratory tests will be reported on Form TL-26, as outlined in Section 800. (Note exceptions for cylinders tested on portable compression testing machines, as outlined in Paragraph (e) above.)

Recorded data for compressive strength specimens shall include, but not be limited to, the following details:

(1) Date and time of day.

(2) Class of concrete.

(3) Percent of free moisture in coarse aggregate.

(4) Percent of free moisture in fine aggregate.

(5) Water-cement (W/C) ratio (gals. per bag).

(6) Cement factor (bags per cubic yard).

(7) Percent of entrained air.

(8) Amount of slump or ball penetration.

(9) Temperature of plastic concrete.

(10) Average air temperature at time of casting.

(11) Average temperature during curing.

(12) Location of point of deposit in the structure.

(13) Types and amounts of admixtures.

Sec. 411.03 QUESTIONABLE CONSTRUCTION PROCEDURES — Section 219.13 (b) (4) requires that anytime the Inspector observes poor practices or curing deficiencies on the job, he shall note such deficiencies on Form TL-28 and shall immediately notify the Contractor's representative and the Engineer of his action and the notation made. The Engineer shall then decide if additional inspection and tests are to be made on the hardened concrete prior to acceptance of the concrete involved.

Sec. 412.01 GENERAL — Although concrete pavements depend upon their flexural strength, not their compressive strength, to carry the loads to which they are subjected, under the revised specification the quality of the concrete itself is controlled by the tests and procedures given in Section 219, which include compressive strength tests.

In addition to these requirements for concrete quality, beam tests are utilized to determine the time at which pavement concrete has attained sufficient strength to sustain ordinary traffic, and therefore may be opened for use. Concrete pavements will also be checked for depth and compressive strength by drilling cores from the completed pavement. This drilling will be performed by the Central Office Laboratory.

Sec. 412.02 FLEXURAL STRENGTH SPECIMENS— Flexural strength specimens are to be made by casting fresh concrete in beam molds. Records shall be kept of all concrete beams cast on pavement jobs, in accordance with Paragraph (e) below.

(a) Sampling — Concrete for the beam test specimens shall be sampled from the batch immediately after it is deposited on the subgrade, in accordance with AASHO Specification, Designation: T 141, or as modified herein.

An air content and a consistency test, as outlined in Sections 409 and 408 respectively, shall be made of the same batch of concrete from which the flexural beam is cast, and the data recorded as for the other tests. The batch of concrete selected for the beam test may be the same as a randomly selected batch to be tested for compressive strength and other quality assurance tests.

(b) Molding and Curing—Molding and curing of the flexural specimens shall be conducted, as outlined in AASHO Specification, Designation: T 23, or as modified herein.

Molds for the casting of beams for test purposes are supplied by the District Materials Engineer on each concrete road construction project. These molds are designed to give a beam specimen of such length that, when necessary, 2 determinations of strength can be made on each. The dimensions of the beam are 6" x 6" x 40", and an accurate determination of the area of the cross section shall be made at the point of failure after each test.

The test specimen shall be made as quickly as possible, and the exposed surface shall be treated for the first 24 hours in exactly the same manner as the pavement surface. At the end of 24 hours, or longer if temperature conditions require, the beam shall be removed carefully from the form, marked for identification, and buried flush with the surface of the soil. The top surface shall continue to be cured in the same manner as the pavement surface, until the Inspector is ready to determine the beam strength or modulus of rupture.

(c) Frequency of Sampling—A minimum of at least one complete beam shall be cast for each day's concreting operation.

(d) Testing—Flexural strength of the test specimens shall be determined, as outlined in AASHO Specification, Designation: T 177, or as modified herein.

In cool weather, due to the retarding effect of lower temperature on the strength of the concrete, the first break should be made on the test specimen about 2 weeks after casting. In summer, with prevailing temperatures around 90° F., the first break of the beam may be made in one week. If the modulus of rupture is not as great as required by the specification, another determination should be made several days later, on the remainder of the specimen. Experience will soon indicate at what age the beam will probably have reached or exceeded the required modulus of rupture, and it will rarely be necessary to make a second test on the same beam.

The apparatus furnished for the beam test is composed of a simple hydraulic jack and a yoke to restrain the upward movement of the jack, for the purpose of applying the maximum stress on the center of the specimen along a line at right angles to its axis. The jack is equipped with a gage having a free hand to record the maximum load. A pencil line is drawn 15 inches from one end of the beam, across one side, at right angles to its axis. The beam, with the pencil mark up, is laid on the

2 half-round bearings of the frame, allowing one inch overhang at one end. The jack is placed on the beam, its half-round bearing directly on the pencil line, which should be exactly under the center line of the yoke. The head of the jack is unscrewed until it rests firmly against the underside of the yoke. The load is applied by operating the jack at not more than 900 pounds (gage reading) per minute, after passing the 1800 pound load reading. Up to 1800, the load may be applied more rapidly. As the distance between the beam supports is 24 inches, the modulus of rupture of the 6 inch square beam, in pounds per square inch, will equal 1/6 of the gage reading at the breaking load, in accordance with the formula for modulus of rupture with center point loading as follows:

$$\text{Modulus of rupture, in psi} = \frac{3WL}{2\,bd^2}$$

Where: W = Maximum indicated load, in pounds,

L = Distance between supports, in inches, and

b&d = Breadth and depth of beam, in inches.

With a 6" x 6" x 40" beam, this formula resolves to

$$\frac{72\,W}{432} \text{ or } \frac{W}{6}$$

Therefore, 1/6 of the gage reading equals the modulus of rupture of the tested specimen in pounds per square inch.

(e) Reports—Field data for concrete beams will be recorded and maintained in project records. The information shall include, but not be limited to, the following details:

(1) Date beam was cast.

(2) Class of concrete.

(3) Percent of free moisture in coarse aggregate.

(4) Percent of free moisture in fine aggregate.

(5) Water-cement (W/C) ratio (gals. per bag).

(6) Cement factor (bags per cubic yard).

(7) Percent of entrained air.

(8) Amount of slump.

(9) Temperature of plastic concrete.

(10) Average air temperature at time of casting.

(11) Average temperature during curing.

(12) Type of curing.

(13) Types and amounts of admixtures.

(14) Age at time of test.

(15) Modulus of rupture.

(16) Station number or location.

Sec. 412.03 DEPTH TESTS—Job acceptance depth tests of concrete pavements will be conducted, as outlined in VTM-26. The depths and compressive strengths of the drilled cores will be reported on Form TL-106, as outlined in Section 800. See also Section 401.01 (e) for additional details of coring equipment.

The following section is intended as a guide for interpreting and administering the specifications for concrete. This guide is to be considered as a supplement to the control procedures previously outlined herein. It is not intended to relieve the Inspector of other duties required to obtain proper quality inspection of concrete.

Sec. 415.01 RESPONSIBILITY OF MATERIALS DIVISION–

(a) Mix Design Approval–Concrete mix designs shall be approved or disapproved, as outlined in Section 106.01 (c) and 800, prior to the start of concreting operations.

(b) Personnel Certification–The State Materials Engineer shall direct the administering of examinations and certifications of Batchers, Technicians, and Inspectors.

Written examinations shall be administered by the District Materials Engineers for certification of Department and Industry personnel in their respective Districts. The written examination shall be monitored by the District Materials Engineer or his assistant, and an accurate accounting of all examination papers shall be maintained.

Practical examinations shall be administered under the direction of the State Materials Engineer, assisted by qualified personnel of the District Materials Engineers' staffs performing examinations in Districts other than their own.

All written and practical examinations shall be prepared, graded, and recorded under the direction of the State Materials Engineer.

Re-examination and re-certification will be required 4 years from the date the certificates are issued. The status of the certification for Inspector, Technician, and Batcher is valid only for the specific responsibilities and privileges granted to the bearer and appearing on the certificate issued. If at any time an Inspector, Technican, or Batcher is found incapable of performing his duties as prescribed herein, he is not to be allowed to take part in the production of concrete being batched for State use. The certification issued shall be rendered invalid upon the recommendation of the District Materials Engineer.

(c) Supervision of Certified Concrete Inspectors–The District Materials Engineer and his representatives shall be responsible for supervising the inspection of the condition, handling, storage, and proportioning of all material, performance of control checks and tests at the batching plant, performance of acceptance tests at the point of discharge, and the condition of all plant, trucking, and placing equipment. He shall train and supervise all Department personnel who are involved in any of the above areas of inspection at all batching operations. This statement includes Construction Inspectors and other construction personnel furnished from the projects by the Resident Engineer.

(d) Duties of Certified Inspectors at Batch Plant–Only Certified Concrete Inspectors may be used from the project or the district to serve as Plant Inspectors. Concrete Plant Inspectors shall be instructed by the Resident Engineer, when being sent from the project, to

report to the plant sufficiently in advance of the start of batching operations to perform the preparatory control checks, as described herein.

The Plant Inspector shall never assume, by act or word, the responsibility of batch control adjustments, calculations, or the setting of dials, gages, scales, and meters.

The Plant Inspector shall issue batch reports, as outlined in Section 800, for only those loads of concrete which have been batched in strict accordance with specification and special provision limits and criteria. He shall also keep a plant diary of daily plant operations. He has the authority and the responsibility to question, and where necessary, reject any operation or sequence of operations which are not performed in accordance with specifications and special provisions.

For additional duties of Plant Inspectors, see Section 109.02.

(e) Duties of Inspectors at Point of Discharge—An inspector shall be present at the job site during the discharge and placement of concrete to properly inspect these operations. The Department shall detect and reject, at the point of discharge, all concrete which fails to meet the range specified for consistency and air content. Concrete having an air content less than the minimum value specified is to be considered equally objectionable as concrete having an air content greater than the maximum value allowed.

Concrete shall be sampled and tested for consistency and air content in accordance with Sections 408 and 409.

If, during discharge, the Inspector observes an appreciable increase in the consistency of the concrete, especially when the initial test revealed the consistency to be a specification borderline, discharge shall be halted and a recheck test performed. The remainder of the load shall be rejected if the results of the test(s) fail to meet the allowable limits specified.

When any ingredient is to be added in whole or in part at the job site, this is considered a batching operation and the requirements for a Certified Inspector will be maintained. If the *only* ingredient to be added at the job site is cement, and if it is to be added in *whole bag* increments, the presence of a Certified Inspector will be necessary to verify that the correct quantity of cement is added. (See Section 415.02 (e) below for certified personnel exceptions in the case of adding water at the job site.)

(f) Inspection of Plant, Equipment, and Personnel—

(1) Initial Plant Inspection A program of regular but unannounced inspection shall be scheduled and supervised by the District Materials Engineer at all portland cement concrete plants supplying concrete for State work. This inspection shall be conducted at any plant initially setting up and starting production, and at least once per year thereafter or as required. The purpose of this inspection is to determine that the plant equipment and personnel meet specification requirements. A record shall be prepared on a check list type form of all items covered during the plant inspections by the District Concrete Technician.

A personal contact should be made with each producer who intends to furnish concrete and who has had compressive strength problems in the recent past and who, because of certain problems known to exist, is likely to experience low compressive strengths again. It should be determined in the contact the additional control procedures the producer will institute in an effort to avoid such problems in the future.

(2) Regular or Routine Plant Inspection—In addition to the initial or annual inspections, a program of regular inspection of portland cement concrete plants shall be conducted by personnel of the District Materials Engineer's staff and by Central Office Materials personnel. The inspections are to be completely unannounced and are to be conducted for the purpose of determining whether or not specifications and instructions are being followed by contractor and Inspector personnel in the production, sampling, testing, and inspection of portland cement concrete.

The frequency of these latter plant inspections should be related to the overall quality of the plant equipment and competence of the plant personnel. Plants, that have a record of continually producing good materials and of being in excellent condition and manned by well trained personnel, might be inspected by the Materials Division's Technicians as seldom as once a year. However, plants with poor records should be inspected more often. Periodic inspection of all plants at the same frequency regardless of record is *not* recommended. Inspectors assigned to the plants will be responsible for daily inspection of the plants. Any unusual conditions encountered by the Plant Inspector should be reported to the District Materials Engineer.

A plant inspection report is to be issued on the forms available for this purpose immediately upon completion of this inspection. The forms are to be completely filled out by the District or Central Office Materials Personnel conducting the inspection, noting any and all specification discrepancies and any corrective action taken by the inspection personnel. In addition to copies of the report retained for District use, copies of plant inspection reports shall be forwarded to the Director of Engineering, the State Materials Engineer, and the State Construction Engineer.

Unfamiliar Department and Industry personnel shall be requested to show evidence of their certification to visiting representatives of the Materials Division.

(3) Inspection of Testing Equipment and Procedures—Periodically, as conditions and personnel proficiency warrant, inspections are to be conducted by personnel from the District Materials Office of the calibration of plastic cement concrete testing equipment and the testing procedures of project personnel. The purpose of this inspection is to improve proficiency and attain uniformity in the use of the equipment throughout the State. An error in testing of plastic concrete may mean rejection of a large amount of material or acceptance of material that does not meet specifications.

An inspection report is to be issued on forms available for this purpose by the person conducting the inspection and signed by this person and the Inspector whose procedures have been checked. Copies of the report are to be forwarded to the Director of Engineering, the State Materials Engineer, the State Construction

Engineer, the District Engineer, and the District Materials Engineer.

(g) Sampling and Inspection of Materials–Plant Inspectors shall be maintained at all plants supplying portland cement concrete for State use, with one exception as follows. When the anticipated yardage of miscellaneous portland cement concrete (all concrete, except pavement, prestressed, and structural) is 50 cubic yards or less per day, only intermittent plant inspection is required. Under this system, the producer shall state on the delivery ticket, accompanying each load, the class of concrete, and weight of cement, aggregate, water, and amount of admixture used in the batch at the time of batching.

In addition to the normal job acceptance sampling of cement and aggregates, progress record samples shall be taken by the District Materials Engineer's representative, specially delegated for this purpose, from stockpiles and storage bins at the ready-mix plant, batch plant, or job site. The samples shall be clearly identified as "Progress Record Samples" and submitted for test to the District or Central Office Laboratory, as outlined in Section 206. The frequency of progress record sampling of these materials shall be as outlined in Section 206, following instructions, as set forth in Section 202.04.

The Plant Inspector shall make visual examinations of the aggregate stockpiles throughout the batching operation, and shall take whatever action is indicated consistent with his understanding of the specified quality of the materials. The following observations for physical characteristics shall be made by the Inspector:

The cement shall be examined for hardened or hydrated cement lumps.

Coarse aggregate shall be inspected for particle coating, segregation, presence of organic and/or soft particles, aggregate in less than saturated surface-dry condition, and any other detrimental characteristics.

Fine aggregate shall be inspected for the presence of clay, presence of organic material, highly variable moisture condition, and any other detrimental characteristics.

Water shall be examined to determine if it is muddy or otherwise contaminated, as evidenced by floating substances, peculiar color, or odor. Water from sources, which include ponds, streams, rivers, etc., should be carefully examined.

During handling of materials, the following items shall be carefully observed:

Aggregate shall be examined for contamination with foundation material upon which the stockpile is built, during removal of aggregate from the stockpile. Aggregate shall be examined for spillage or overrun into adjoining aggregate bins during loading of plant bins. Admixtures shall be examined to determine if there has been a thorough agitation before being dispensed in each day's batching operation. The admixtures shall be examined for liquid separation, differential concentration, and/or fluxuating air content or set retardation.

(h) Reports The Certified Concrete Inspector located at the batch plant shall prepare and distribute Form TL-28 for each load of concrete batched for State work at his plant, as outlined in Section 800. He shall also keep other records, as outlined for concrete herein, including a plant diary, as outlined in Section 800.

(i) Compressive Strength Failures — Any time that compressive strength values less than the class design strength occur in ready-mix concrete, an investigation shall be made by the District Materials Engineer or his representative. The investigation should seek to resolve the following questions:

(1) What is the probable cause(s) of the low test result, based upon visual examination of the test specimen? Check the appearance of the hardened cement-sand matrix to determine if (1) there is excessive water and normal air content, (2) there is excessive air and normal water content, or (3) there is excessive water and air content. Check to determine if the specimen failure was essentially in (1) the aggregate-cement matrix bond, (2) the cement matrix, or (3) in both the aggregate and cement matrix.

(2) Is the cylinder representative of the quantity of concrete mix? Determine when the cylinder was moved with respect to probable initial set. Determine if the location of storage was such that, during initial set, the cylinder was subjected to the vibrations of construction equipment. Determine if the cylinder was stripped from its mold in less than 24 hours. Determine if the temperature was controlled during storage. Review the data recorded on Form TL-28. Visit the concrete plant and check especially the condition of the drum blades of the truck which supplied the concrete from which the cylinders were made. Check plant operations to determine if possible whether or not human error occurred in the selection of or setting of the quantity of cement to be weighed, or malfunction occurred in the operation of the scales, either or both of which could have caused deficient cement content.

(3) What recommendations are indicated from the investigation relative to coring the structure?

(4) What action was taken or is indicated in order to avoid recurrence of future compressive strength failures resulting from the cause(s) discovered in this investigation?

(j) Establishing Quality of Concrete in Structures — The acceptance of concrete is normally based on compressive strength test results. As indicated in Section 411.03-f, concrete is acceptable at full bid price if no more than 10 percent of the total strength values fall below the minimum design strength, f'_c. The specification also sets a rejectable limit for concrete. That is the value for which 40 percent of the strength values would be below f'_c. A reduced payment is made for concrete between those two limits, since such concrete could have poorer performance than that fully meeting the specifications, but the cost of replacing the structure does not justify its removal. Unless a definite cause for a cylinder failure has been found, due to its not having been sampled, molded, handled, cured and/or tested properly, a unit of structure for which strength results are at or below the rejectable level shall be cored where indicated by the Bridge Engineer. The cores shall be tested at an age of 28 days or older, and the test results shall be considered to represent the quality of the concrete in that unit of structure. Results of impact hammer tests will not be recognized as an official control or investigation tool. It is possible that the results obtained with this instrument may be too radical and depend on constant calibration and uniform individual technique. Therefore, control, acceptance, or rejection of structures will not be based on the results obtained with this instrument.

Financial responsibility for necessary replacements of sub-quality units, established by test cores, will be assigned to the contractor, when the placement, finishing, protection, and/or curing operation(s) was not conducted in accordance with specifications and special provisions.

When average core strengths indicate that concrete is at least 85 percent of the required strength for laboratory cured cylinders, the strength of the hardened concrete will be considered satisfactory and the contractor will be paid on the basis of the core strengths.

Sec. 415.02 RESPONSIBILITY OF CONCRETE PRODUCER–

(a) Materials–The quality control and condition of all materials used in concrete, as well as all necessary adjustments required in using the materials, shall be the responsibility of the concrete producer, in accordance with Section 219 of the Road and Bridge Specifications.

(b) Personnel–All sources supplying concrete to the Department shall be required to have present during batching operations certified personnel, as outlined in Section 219 of the Road and Bridge Specifications. (See also conditions for waiver of this requirement.)

(c) Equipment–Requirements for approval of concrete plants of particular note, in addition to others outlined in the Road and Bridge Specifications, are as follows:

(1) Suitable equipment shall be available at the plant for determining aggregate moisture, air content, and slump.

(2) The amount of air-entraining admixture shall be added within a limit of accuracy of 3 per cent, and shall be dispensed by means of an approved graduated transparent device to the mixing water as the water is being put in the mixer.

(d) Performance of Control Tests by Concrete Producer–All control tests and batch adjustments are to be performed by the Certified Concrete Technician, with the exception that the Certified Concrete Batcher may make aggregate moisture tests and adjust aggregate design weights to batch weights, provided that this authority is so noted on his certificate.

The certified employees of the concrete producer are expected to perform aggregate moisture tests, air checks, and consistency checks prior to, or as an individual operation to, the performance of these tests by the Plant Inspector.

The Inspector shall not provide the Technician or Batcher the results of his moisture determinations until after the tests have been properly performed by the producer's certified employee.

In the event that the two individual tests do not agree, independent recheck tests shall be run using material from the one large sample.

2180 *(e) Adding Additional Water or Other Ingredients to Batch at Job Site*—Should the contractor desire greater workability in concrete, he should notify the producer in order that the proper adjustments can be made at the plant by the Certified Concrete Technician.

When the mixing water is to be added to the batch at some point other than at the plant along with the other ingredients, the operation shall be performed by the producer's Certified Concrete Technician and/or Batcher, with exceptions noted below. The water shall be measured and discharged in accordance with the Road and Bridge Specifications.

For those load(s) already on the job or in transit to the job which lack sufficient workability, the contractor may assume the responsiblity for the adding of additional water, or he may obtain authorization to do so from the producer, provided the maximum water content or slump specified is *not* exceeded.

Neither the Plant Inspector nor the Project Inspector shall direct the adding of water to a batch of concrete, but shall reject any load to which water has been added in excess of the maximum water content or slump specified.

It is intended that the ***main*** volume of mixing water be added at the batch plant, under the supervision of a Certified Technician or Batcher and recorded by a Certified Inspector on Form TL-28. It will be permissible, however, to withhold during initial mixing up to *one gallon per cubic yard,* if required. Upon arrival at the job site, this water withheld at the plant should be added to the mix, *just prior to discharge,* provided that the ***maximum mix design water content is not exceeded.*** This water may be added in more than one increment, until the desired consistency is obtained. *This* water adjustment will require *no* certified personnel to be present. However, this adjustment of water will still be the responsibility of the contractor.

If it is found to be necessary to withhold more than one gallon of water per cubic yard of concrete at the batch plant, then the mix should be redesigned immediately. If the maximum allowable water-cement ratio and slump are not exceeded, then the full amount of all ingredients specified in the approved mix design should be added, or else the yield will be affected.

In cases where additional water that has been withheld at the batch plant is added at the job site, it will be necessary to provide some additional mixing at the job, in accordance with the Road and Bridge Specifications. It should also be noted that *no* mixer water is to be used for the washing of any equipment during the period of the batching operation.

With the above noted exception, when any ingredient is to be added in whole or in part at the job site, this is considered a batching operation and the requirements for a Certified Technician or Batcher will be maintained. However, if the *only* ingredient to be added at the job site is cement, and if it is to be added in ***whole bag*** increments, the presence of a Certified Technician or Batcher will ***not*** be required. (See also Section 415.01 (e) for Certified Inspector requirements in this case.)

Mixing will begin immediately after all ingredients are in the drum. The provision for a 30 minute delay after the cement comes into contact with moisture *only* applies where the mixing water will be added later. When all ingredients are added at one time, mixing should commence immediately.

See also Section 405 for details of designing and batching mix.

SECTION 416 SUMMARY OF MINIMUM JOB ACCEPTANCE SAMPLING REQUIREMENTS

Following is a condensed tabulation showing the minimum requirements for job acceptance testing of portland cement concrete. See also Section 205 for additional details governing minimum sampling.

MINIMUM JOB ACCEPTANCE SAMPLING REQUIREMENTS

MATERIAL AND TEST	ROAD AND BRIDGE SPECIFICATION REFERENCE	RATE OF SAMPLING	LOCATION FOR SAMPLING	REMARKS
1. Base and Pavement - (a) Air Content	219.14	One per hour, and when making flexural specimens	At job site	Pressure Method to be used at beginning of job to correlate Chace results, after which only Chace Method is required. However, should Chace indicator indicate concrete to be rejected, rejection must first be confirmed with test by Pressure meter. Enter results on Form TL-28 and/or in project materials record.
(b) Consistency - (1) Slump Test	219.14	Two (2) daily, and when making flexural specimens	Same as Item 1 (a).	Enter results on Form TL-28 and/or in project materials record. If test on any batch fails, recheck batch immediately by Slump Test.
(c) Depth	321.20	See VTM-26.	Same as Item 1 (a).	Drilled by Central Office Laboratory. Also checked for compressive strength. Reported on Form TL-106.
(d) Flexural Strength	321.08, 321.19	One per day.	Same as Item 1 (a)	Slump and Air Content Tests (Pressure or Chace) to be made from same batch. Enter data in project materials record.
(e) Moisture of Aggregates		Two (2) daily or as required.	At ready-mix plant, batch plant, or job site.	Enter test results on Form TL-28 and/or in project materials record.
2. Structural (Bridges, Box Culverts, and Retaining Walls) (a) Air Content	219.14	At start 1 per truck. Thereafter, 1 per 5 trucks (randomly selected) and 1 per batch when making compressive strength specimens.	Same as Item 1 (a).	Same as Item 1 (a). Test results recorded on Forms TL-13, TL-26, TL-28 and/or in project materials record.
(b) Consistency (1) Slump Test	219.14	Same as 2(a).	Same as Item 1 (a).	At least 2 of tests daily shall be by Slump Cone method. Remainder of tests may be by the Ball-Penetration method. If test on any batch fails by either method, recheck batch immediately by Slump Test. Test results recorded on Forms TL-13, TL-26, TL-28, and/or in project materials record.
(2) Ball-Penetration Test		One per batch (truck). See Remarks	Same as Item 1 (a).	
(c) Compressive Strength	219.15	Except bridge decks. One set of 3 cylinders per 100 cubic yards from same batch, with minimum of 2 sets of 3 each per structure per class of concrete. Any one set to be made from same batch. Bridge decks: One set of 3 cylinders per 50 cubic yards with minimum of 2 sets for deck.	Same as Item 1 (a).	Additional back-up cylinders recommended in cool weather, as outlined in Section 411.02 (d). One set of 2 cylinders per structure to be tested in Central Office Laboratory. Slump and Air Content Tests (Pressure or Chace) to be made from same batch. Field data and test results recorded on Forms TL-13, TL-28, and TL-26.
(d) Moisture of Aggregates		Same as Item 1 (e)	Same as Item 1 (e).	Enter test results on Forms TL-13, TL-28, and TL-26.
3. Prestressed - (a) Air Content	219.14	Same as Item 2 (a), except when casting with batches of 4 cubic yards or less, only one test at beginning of casting operations and when making compressive specimens will be required.	Same as Item 1 (a)	Same as Item 2 (a). In addition, test results entered on Form TL-62.

MINIMUM JOB ACCEPTANCE SAMPLING REQUIREMENTS - Continued

MATERIAL AND TEST	ROAD AND BRIDGE SPECIFICATION REFERENCE	RATE OF SAMPLING	LOCATION FOR SAMPLING	REMARKS
Continued)				
(b) Consistency	219.14	Same as Item 2 (b), except when casting with batches of 4 cubic yards or less, only one test at beginning of casting operations and when making compressive specimens will be required. In this case, Slump Cone method shall be used.	Same as Item 1 (a).	Same as Item 2 (b). In addition, test results entered on Form TL-62.
(c) Compressive Strength	219.20	Two (2) sets of 3 cylinders each (minimum of 6 cylinders) per concreting operation to be cured with prestressed units. Each set shall represent separate batch sampled. In addition, one set of 3 cylinders to be made from same batch and same composite sample as one of sets noted above per concreting operation, with minimum of 3 per 50 cubic yards. These latter samples to be given standard moist cure.	Same as Item 1 (a).	Slump and Air Content Tests (Pressure or Chace) to be made from same batch. Two (2) of 3 moist cured cylinders to be tested in District Laboratory. One of each set may be tested in Plant Laboratory. Field data and test results recorded on Forms TL-13, TL-28, TL-26, and TL-62.
(d) Moisture of Aggregates		Same as Item 1 (e).	Same as Item 1 (e).	Enter test results on Forms TL-13, TL-28, TL-26, and TL-62.
Miscellaneous (All Concrete Except Items 1, 2, and 3) -				
(a) Air Content	219.14	One per day, and when making compressive specimens.	Same as Item 1 (a).	Same as Item 2 (a). Also, caution should be exercised against setting routine times for taking tests, to avoid predictions as to which load is to be tested.
(b) Consistency - (1) Slump Test	219.14	Same as Item 4 (a).	Same as Item 1 (a).	Same as Item 2 (b). Exercise same precautions as in Item 4 (a).
(c) Compressive Strength	219.15	One set of 2 cylinders per 250 cubic yards, with minimum of one set of 2 per project. Any one set to be made from same batch.	Same as Item 1 (a).	Slump and Air Content Tests (Pressure or Chace) to be made from same batch. Field data and test results recorded on Forms TL-13, TL-28, and TL-26. In the case of projects containing less than 50 cubic yards of miscellaneous concrete, the District Materials Engineer may waive the requirement for compressive specimens, provided this is documented in project records. Cylinder tests for same class of concrete for other projects being supplied on same day from same plant may also be used to satisfy testing requirement.
(d) Moisture of Aggregates		Same as Item 1 (e).	Same as Item 1 (e).	Same as Item 2 (d). When anticipated yardage for this type concrete is 50 cubic yards or less per day, only intermittent plant inspection is required. Under this system, producer shall state on delivery ticket accompanying each load the class of concrete, and weight of cement, aggregate, water, and amount of admixture used in batch at time of batching

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APPENDIX E

VTM-XX* PROCEDURE FOR RANDOM SELECTION OF PORTLAND CEMENT CONCRETE BATCHES TO BE SAMPLED FOR ACCEPTANCE TESTING

Scope:

This method describes a procedure for the random selection of batches of concrete to be used in acceptance testing as required in Section 219 of the Road and Bridge Specifications of the Department.

As an alternate to this procedure, ASTM Method D3665 or any system that generates a series of two digit random numbers equivalent to the number of sublots to be sampled may be used.

Determine Number of Sublots:

From the plans and specifications or contract involved, determine the number of sublots to be sampled and tested for the concrete lot to be placed using the frequency of sampling prescribed in Section 219.14(c).

For example, if it is known that a bridge deck will require 480 cubic yards, the number of sublots will be 10; that is, 50 cubic yards plus the remainder for the tenth sublot.

For structural concrete other than bridge decks, a sublot is defined as 100 cubic yards. Thus, 480 cubic yards would constitute 5 sublots for such concrete.

Determine Load to be Sampled:

Place 10 discs or washers, numbered 0 through 9 in a suitable container. Shake and, without looking, draw a disc. This number is then the first digit of the percentage. Replace the washer and repeat the process for the second digit of the percentage.

For example, if a 6 and a 4 are drawn, the acceptance sample is taken from the truck that contains the cubic yard which represents the sixty-fourth percentile of the sublot; that is, if the sublot size is 50 cubic yards, the sample is taken from the truck

*Number to be assigned.

containing the thirty-second cubic yard. If the sublot size is 100 cubic yards, take the sample from the truck containing the sixty-fourth cubic yard of the sublot.

At the end of a job where a full sublot will not be placed, compute the percentage of the sublot in the usual manner. If the percentage determined by the random drawings exceeds the amount of concrete to be placed, do not sample. If it is within the amount to be placed, treat it as an additional sublot and make the usual tests.

For example, the random digits drawn are 5 and 4. Thus, the percentage is 54. If the last sublot to be placed represents more than 54 percent of the usual sublot size, take the acceptance sample from the truck containing the fifty-fourth percentile. If less than 54 percent of the normal sublot is to be placed, do not sample.

Repeat the selection process to generate the two-digit random number for the percentage of the sublot for as many times as necessary for the number of sublots to be sampled.

Such numbers may alternatively be generated from a table of random numbers or other valid statistical procedures.

Sampling:

The sample of concrete to be taken from the designated truck shall be taken in accordance with AASHTO Method T-141.

Precautions:

The truckload to be sampled for each sublot should be established prior to beginning the concrete placement. However, this information should be kept confidential until the load to be sampled arrives on the job.

While the particular randomizing method to use is a matter of convenience or judgement, it is emphasized that arbitrarily selecting a load for sampling other than the one selected by the randomizing procedure must not be permitted. Only when a load designated as an acceptance sample is rejected and removed from the job should a change be made. In this case, the next load placed automatically becomes the load for acceptance sampling.