THE VIRGINIA DEPARTMENT OF TRANSPORTATION'S STATISTICAL SPECIFICATION FOR HYDRAULIC CEMENT CONCRETE

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ABSTRACT

This report reviews some of the principles relating to the application of statistical concepts to be used in the quality assurance and acceptance testing of hydraulic cement concrete. The problems encountered in developing a workable system without a substantial increase in the testing and inspection personnel for the Virginia Department of Transportation are discussed as well as the significant changes instituted by the special provision for Section 219 of the VDOT Road and Bridge Specifications.

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INTRODUCTION

In February 1989, the Virginia Department of Transportation (VDOT) implemented special provisions for the acceptance of hydraulic cement concrete. Although it is customary to refer to these special provisions as a "statistical specification," it would be more accurate to say that the changes adopted incorporate certain statistical procedures for concrete acceptance but require the retainment of a considerable degree of engineering judgment and compromise. Such compromise optimizes the amount and cost of testing in relation to the risks of accepting unsuitable material on highway construction projects.

The special provisions are the culmination of seven years of cooperative effort among several units of the Virginia Department of Transportation including the Research Council, the Materials Division, the Construction Division, and other personnel of the Department. Because a number of reports have been written, each containing slightly different recommendations, this review has been prepared to avoid confusion and to provide the rationale for the provisions finally adopted.

DIFFICULTIES ENCOUNTERED

VDOT was one of the first state highway agencies to adopt statistical quality assurance procedures for asphalt concrete construction, but it has proved much more difficult to incorporate similar procedures for hydraulic cement concrete. Other states have also encountered difficulties.

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--do not exist at the time concrete is placed; 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 lead to an indication that the concrete is not in 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 difficulties 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 fresh concrete. However, an increase in the water-cement ratio can result in a low-strength material and a high degree of porosity, which results in low resistance to penetration of deicing salts. This leads to corrosion of reinforcing bars and subsequent spalling. Also, different combinations of ingredients can result in different rates of strength development. Thus, for different mixture proportions, strength determinations at early ages do not always represent the same relation to the ultimate strength. These considerations make it essential that, for good results, hydraulic cement concrete be proportioned by persons knowledgeable in concrete technology and its placement be supervised by someone capable of exercising a high degree of on-the-spot judgment.

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 possibility that test data based on cylinders or other fabricated test specimens may not accurately indicate the actual characteristics of the hardened concrete in the pavement or structure. This same uncertainty exists regardless of how much test data are available or how the data may be analyzed. In view of these difficulties, it is appropriate to consider what is gained by this statistical approach, since the inspection and acceptance procedures that have been used for years have been basically successful.

THE PURPOSE OF SPECIFICATIONS

The purpose of any specification is to describe the product wanted. The quality assurance program (the testing and inspection) is to determine if the wanted product was furnished. If the product is a barrel of nuts and bolts, it is fairly simple to look them over, test a few, and if they are not wanted, send them back. For the concrete in a bridge deck or the foundation of a structure, the answer concerning compliance is not available for a month, and by that time much has happened on a project. It is not possible to say "take it back" or even to tear out and replace the bad concrete without affecting the total project.

For highway construction, the principle of "reasonable conformity" has been recognized. This can be represented schematically as follows:

Bad	Borderline	Good

Instead of simply a good and a bad zone, a gray area of borderline material or product is recognized. In this area, the product is deficient in some respects but the deficiency is not sufficient to warrant complete rejection and replacement. In the bad area, the product is unacceptable.

Now, all that is necessary is to define the boundary between each zone--and this is where the egg hits the fan!

The first thing that must be done is to take samples and make measurements--but how many? How accurate are the test results? How much material does the sample represent? When does borderline material become bad material?

In the old days, engineering judgment was used to arrive at the answers to these questions. This works well when experienced reasonable persons are on the job, but it can create problems when the judgment is flawed. In a dispute, it becomes one person's judgment against another's. Problems also arise when the same degree of discrepancy is handled differently in different cases.

Under the statistical approach, an effort is made to obtain definitive answers to these questions by defining the boundary between each zone. The boundary will be the same for everyone and will also represent a cost-effective use of inspection and testing personnel.

A number of standard statistical principles are available, such as acceptance quality levels, rejectable quality levels, consumer and producer risks, and operating characteristic curves. However, research and pilot studies conducted by the VDOT demonstrated that strict adherence to these approaches would result in unacceptable increases in the amount of testing required. Accordingly, judgments were necessary to devise a workable plan. The following discussion summarizes the major changes implemented by the special provisions (a copy of which is included as the Appendix). The rationale for each change is also discussed.

CHANGES IN CONCEPTS

Define Minimum Strength (f'_c)

The first change is that the design minimum 28-day compressive strength, f'_c, is not the minimum acceptable value or even the minimum acceptable average of several tests results.

Under the statistical procedure, f'_c is defined as the minimum value below which not more than 10 percent of the strength values will lie, assuming that the population of all the strength results have normal distribution. Consequently, the average of the acceptable population must be $f'_c + 1.28\sigma$, where σ is the "true" standard deviation of the population, a value that can only be estimated, and one that will vary somewhat from concrete producer to concrete producer depending on the degree of control exercised and the characteristics of the ingredients being used.

It is obvious that the concrete producer must proportion the mixture so that the average strength of test cylinders is above f'_c. This is not different from present practices, but the statistical concept provides a means for estimating the needed average provided a good estimate of the standard deviation of the production is available.

Although no specific requirements for a target average for preliminary tests was adopted, historical data show that production from a single plant will have a standard deviation in the range of about 500 to 800 psi. Thus, the target average for the production should be 600 to 1,000 ($1.28 \times \sigma$) above f'_c for the class of concrete desired.

Definition of a Lot and Frequency of Tests

A second important change of the statistical provisions is that a day's production of concrete from a specified plant using the same mixture proportions and sources of ingredients constitutes a lot. The samples taken and tested for the lot are then considered the basis for accepting that lot. Although there must be a minimum of three samples in order to calculate an estimated standard deviation of a lot, and thus fully apply statistical concepts, studies showed that for the concrete projects being built by VDOT, strict adherence to this minimum for each lot would unnecessarily increase the amount of testing required. Accordingly, a schedule was established that would retain approximately the same amount of testing as is currently required.

This schedule is:

- For bridge deck concretes--a minimum of three samples per lot (day's production) regardless of lot size.
- For all other paving, structural, or incidental concrete, the minimum number of tests per lot is as follows:

Lot Size in Cubic Yards	Minimum Number of Tests
0- 50	0
51-150	1
151-274	2
More than 274	3

The Acceptable Average for a Lot

The special provisions define the boundary line between good and borderline material as the acceptable average X_{ac}. Statistically, this is based on the assumption that the test values will have a normal distribution and that the approved mixture proportions will yield strength values so that not more than 10 percent are below f'_c. However, for individual lots, allowance is made for possible sampling and testing variability, and the required average is set so that there is only a small chance that material actually meeting the specification will be classified as deficient because of normal sampling and testing variability.

The equation for the acceptable average is:

$$X_{ac} = f'_c + ks$$

where

s is the standard deviation of the test samples from the lot

k is the acceptability constant based on the statistical noncentral t program. It varies with the number of samples (n) tested for the lot and the statistical risk of rejecting good material. For a risk of 1 chance in 20 (5 percent), values of k are:

No. Samples	k
3	.335
4	.444
5	.519

Since the standard deviation of a lot cannot be estimated when fewer than three samples are taken, the acceptable average is set by judgment and past experience at $f'_c + 100$ when two samples are tested and at f'_c when only one sample is tested.

The Rejectable Average for a Lot

A number of ways were tried to define statistically the boundary between the bad and borderline material. However, because of the small number of tests involved, unrealistic values are obtained by strict adherence to quality level and risk concepts based on operating characteristic curves. In consideration of these problems, the rejectable average was established by judgment at 500 psi below the acceptable average.

Adjusted Payment Schedule

The special provision then establishes provisions for differences in payment for the concrete depending on the lot average. For all lots that average X_{ac} or above, the full contract price is paid for the lot. If the lot average is in the borderline zone between the acceptable and rejectable average, the payment is reduced according to the amount the average is below the acceptable value. This reduction is 0.0002 for each psi (2 percent for each 100 psi) below the acceptable average up to 300 psi. When the deficiency is between 301 and 500 psi, the pay factor is reduced 0.0600 plus 0.0007 for each additional psi the deficiency exceeds 300 (see Figure 1).

When the test result is below the rejectable average (greater than 500 psi deficiency), an investigation into the cause of the low result is to be made, and if necessary, cores of the area representing the lot are to be taken. Procedures are established for acceptance on the basis of the results of tests on the cores.

Advantage of New Approach

Under the special provision, it is expected that the concrete furnished to VDOT will be of the same overall quality as that furnished under present procedures, and for projects of the usual size, the amount of testing will be about the same. For larger projects such as paving, the amount of testing under the new provisions would probably be decreased.

The principal advantage to VDOT and to the concrete producers alike is that the implementation of the new acceptance procedure establishes an automatic and uniform method for handling noncomplying test results. Under this system, essentially all the problems relating to low-strength tests for concrete supplied to VDOT over the past 5 to 6 years would have been automatically settled. In rare cases of serious discrepancies, investigations of the causes and case-by-case decisions would be needed, as is now the case.

Under the special provision, concrete producers that now produce good quality concrete and have acceptable quality control procedures are not likely to be penalized. However, the possibility of such an occurrence serves as an incentive for maintaining good control and a deterrent to temptation to cut corners. The producer supplying quality concrete is also protected against unfair competition from possible low bidders supplying noncomplying products.

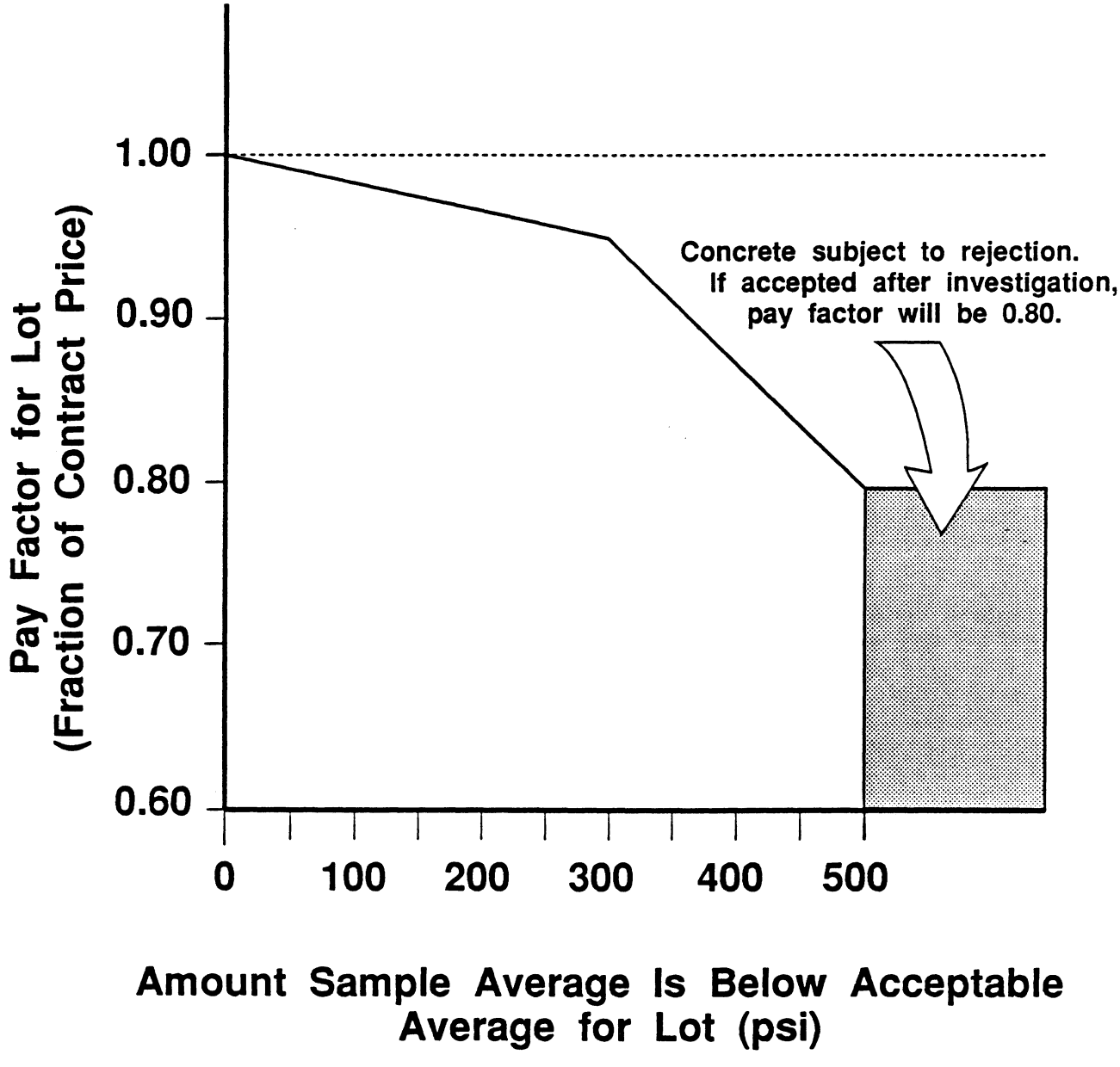

Figure 1. Payment reduction schedule.

APPENDIX

APPENDIX

VIRGINIA DEPARTMENT OF TRANSPORTATION
SPECIAL PROVISION FOR
SECTION 219

February 1, 1989

Section 219 of the Specifications is amended as follows:

Section 219.05(a) is amended to completely replace the second paragraph with the following:

Scales used for weighing aggregates and cement shall conform to the sensitivity and accuracy requirements as defined by the National Bureau of Standards Handbook No. 44 for Specifications Tolerances and Requirements for Commercial and Weighing Devices. Such scales shall also be approved and sealed by the Virginia Department of Agriculture and Consumer Services Weights and Measures Bureau, or other approved agencies within the previous 12 months and upon being moved. 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 weights shall be calibrated by the Virginia Department of Agriculture and Consumer Services when new and whenever there is visible evidence the weights have been damaged.

Section 219.07 is amended to delete the second sentence of the third paragraph and to delete the eighth paragraph.

Sections 219.08, 219.09, 219.10 and 219.11 are completely replaced by the following:

Section 219.08 High Early Strength Portland Cement Concrete -

When high early strength portland cement concrete is authorized, it shall conform to 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. Acceptance procedures and pay factors shall apply as described herein, except that, where applicable, compressive strengths at 7 days shall be used in lieu of compressive strengths at 28 days.

Section 219.09 Quality Control -

The Contractor shall perform the quality control of concrete, including type and frequency of sampling and any testing deemed necessary to ensure that the concrete produced conforms to the specifications.

The Department shall be provided free access to plant production, test reports and copies of mix designs when requested.

Section 219.10 Acceptance of Hydraulic Cement Concrete -

The Department will sample and test hydraulic cement concrete for acceptance in accordance with the provisions herein.

Concrete which does not conform to 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.

Acceptance of bridge deck, structural, pavement and incidental concrete will be on a lot-by-lot basis as defined below:

(Continued)

(a) Definition of a Lot: For the purposes of this specification a lot is a quantity of concrete manufactured during a single work day under conditions of production that are considered to be uniform and where the source and proportions of all major ingredients are the same. The acceptance tests to be made on a lot for different construction activities are as follows:

1. Bridge Deck Concrete - At least three tests in accordance with Section 219.10(b)3 shall be made on each lot When concrete is placed in 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 concrete in all bridge decks so placed in that day may be considered as one lot and random sampling of sublots shall be conducted in accordance with 219.11, except that at least two samples shall be randomly selected from each bridge deck within the lot and tested in accordance with these specifications.

2. Structural, Paving and Incidental Concrete - Tests shall be made in accordance with the following, based on the volume of the concrete in the lot; however, the Engineer may require more tests on any lot:

Lot size in cubic yards	Minimum number of tests
0-50	0
51-150	1
151-274	2
over 274	3

(b) Inspection and Testing

1. Temperature: The Contractor is responsible for furnishing concrete within the temperature ranges established in Section 219.13. However, when considered necessary, the Department's representative may determine the temperature of any batch of concrete immediately after delivery to the job. All batches with temperatures not in compliance with Section 219.13 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. 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 219.11 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 404, the inspector will note such observed deficiencies in the project records and shall immediately notify the Contractor's representative of his action and the notation made. In these cases, additional inspection and tests on the hardened concrete may be made and the Engineer may base the acceptance for strength of the concrete on the strength of cores. The average core strength, based on five or more cores, divided by 0.85 shall be considered the equivalent cylinder strength. The acceptable average shall be as determined in Section 219.15 except that the core strength divided by 0.85 shall be used in lieu of the cylinder strengths.

(Continued)

Section 219.11 Sampling and Testing -

(a) Initial Sampling and Testing: The first batch during each production day shall be sampled and tested by the Contractor for air content, slump, and, when deemed desirable, temperature, prior to discharge into the forms. 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, slump and temperature 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.

(b) Sampling for temperature, slump and air content shall be in accordance with AASHTO T-141, except that composite samples will not be required and samples shall be taken after at least 2 cubic feet have been discharged. 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 also be outside the allowable range, the load will be rejected. If the recheck determination yields acceptable results, another determination will be performed and should these results be within the allowable range the load will be accepted; however, if results are outside the allowable range, the load will be rejected. The air content determination for this recheck shall be made using AASHTO T-152 or T-196.

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

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

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

(c) Acceptance Samples for Compressive Strength: Samples for acceptance based on compressive strength will be randomly selected on the basis of the portion of the workday during which the concrete is placed. Normally, a total of 3 samples shall be taken for each lot - one from each 1/3 of the workday. The portion secured for each test is to be taken after not less than 2 cubic feet have been discharged into a suitable container other than forms. Where conditions warrant and at the option of the Engineer, more than 3 samples may be taken from each lot. When so taken, all results shall be used in judging the acceptability of the lot, except where a cylinder or set of cylinders is obviously faulty.

(Continued)

Section 219.15 Acceptance Criteria -

Compressive strength tests for acceptance will be made at 28 days in accordance with AASHTO T22, T23 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. An acceptable average and a rejectable average compressive strength shall be established for each lot in accordance with (a) and (b) herein. For acceptable concrete, the average strength results shall exceed the values shown by a sufficient amount so that, based on statistical principles and assuming a normal distribution, no more than 10% of the population of strength results will be below the indicated value. The mix proportions shall be set to conform to this requirement, which assuming normal distribution and a known standard deviation, means that the average of the population of concrete strength furnished is at least $f'_c + 1.28\sigma$ where "σ" is the standard deviation of the population.

(a) Acceptable average compressive strength -

1. When the number of tests (n) made on the lot are 3 or more, the acceptable average is determined by the equation:

$$X_{ac} = f'_c + k\,s,$$

where

X_{ac} is the acceptable average of all valid 28 day strength tests made on the lot (a test is considered to be the average strength of three 4" x 8" cylinders),

f'_c is the minimum specified compressive strength at 28 days, and

k is the acceptability constant based on the statistical non-central-t program with an alpha risk of 0.05
(Note: When n = 3, k = 0.335
n = 4, k = 0.444
n = 5, k = 0.519), and

s is the standard deviation for the lot calculated from the test results.

2. When the number of tests made on the lot are 2, the acceptable compressive strength average is $f'_c + 100$.

3. When only one test is made on the lot, the acceptable average compressive strength is f'_c.

4. When no test is made on a lot of concrete, concrete will be accepted on the basis of visual inspection and the concrete producer's certification that the required mix proportions of aggregate and cement have been used and that the maximum water/cement ratio has not been exceeded.

(b) Rejectable average compressive strength -

The rejectable average (X_r) for all lots shall be $X_{ac} - 500$.

(c) Basis of Payment -

1. When the average 28 day compressive strength of the lot is equal to or exceeds the acceptable average compressive strength, the lot will be accepted at the full bid price.

(Continued)

2. When the average 28 day compressive strength of the concrete is between the acceptable and rejectable average, it will be accepted at a reduced pay factor based on the deficiency below X_{ac}.

   The reduced pay factor shall be applied to the number of pay units that would be equivalent to the volume of concrete in the deficient lot. Reductions in payment for other deficiencies shall be based on the reduced price of the lot, if applicable.

   The reduced pay factor shall be calculated as follows:

   If the average 28 day compressive strength of the lot is between 1 and 300 psi below the acceptable average, the pay factor shall be reduced 0.0002 for each psi below the acceptable average.

   If the average 28 day compressive strength of the lot is between 301 and 500 psi below the acceptable average compressive strength, the pay factor shall be reduced by .0600 plus 0.0007 for each additional psi the deficiency exceeds 300 psi.

3. When the average 28 day strength of the concrete is less than the rejectable average, X_r, an investigation will be made to determine the cause of low strengths for the lot and, if deemed necessary, five or more cores will be taken from the concrete in-place constituting the lot.

   Cores so taken will be used to judge the adequacy of the concrete in place. If the average strength of the cores are 85% or more of the design strength, f'_c, the concrete will be accepted with a pay factor of 0.80 of the bid price.

4. In the event cylinders for any lot are conclusively shown to be defective, acceptance of the lot and pay factor determination will be on the basis of core strengths in accordance with Section 219.10(b)4. Acceptance testing based on core strengths will be at the sole discretion of the Engineer.

   In the event the lot proceeding a suspect lot and the lot immediately following a suspect lot are accepted at full bid price, the Engineer may waive coring of concrete in the suspect lot and accept it at full bid price.

Table II-15 is completely replaced by the following:

(Continued)

TABLE II - 15
REQUIREMENTS FOR HYDRAULIC CEMENT CONCRETE

	CLASS OF CONCRETE	COMPRESSIVE STRENGTH AT 28 DAYS, psi	AGGREGATE SIZE NUMBER	NOMINAL MAXIMUM AGGREGATE SIZE	CEMENT MINIMUM GRADE AGGREGATE	MAXIMUM CONTENT LBS./CU.YD. MINIMUM	WATER LBS. WATER/ LBS. CEMENT	CONSISTENCY INCHES SLUMP	AIR CONTENT † PERCENT
A5	Prestressed and other special designs **	5,000	57 or 68	1 in.	A	635	0.49	0 - 4	4 1/2 ± 1 1/2
A4.5	General	4,500	57	1 in.	A	635	0.45	2 - 4	6 1/2 ± 1 1/2
A4	General	4,000	57	1 in.	A	635	0.45	2 - 4	6 1/2 ± 1 1/2
A4	Posts and Rails *	4,000	7	1/2 in.	A	635	0.45	2 - 5	7 ± 2
A3	General	3,000	57	1 in.	A	588	0.49	1 - 5	6 ± 2
A3	Paving	3,000	57	1 in.	A	564	0.49	0 - 3	6 ± 2
B2	Massive or Lightly Reinforced	2,200	57	1 in.	B	494	0.58	0 - 4	4 ± 2
C1	Massive Unreinforced	1,500	57	1 in.	B	423	0.71	0 - 3	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.

† When high range water reducer is used, the target air content shall be increased 1% and the slump shall not exceed 7 inches.

* When necessary for ease in placement, 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 Class A5 concrete is used as the finished bridge deck riding surface, or when it is to be covered with asphalt concrete with or without Class 1 waterproofing, the air content shall be 5 1/2 ± 1 1/2 percent.