

FINAL REPORT

PILOT STUDY OF PROPOSED REVISIONS TO SPECIFICATIONS FOR
HYDRAULIC CEMENT CONCRETE

by

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

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ABSTRACT

This report summarizes the results of a pilot study of the statistical acceptance procedures proposed for adoption by the Virginia Department of Highways and Transportation. The proposed procedures were recommended in the report titled "Improved Specifications for Hydraulic Cement Concrete" and issued in 1983.

This study revealed that practical difficulties would likely be encountered if the initially proposed revisions were adopted. Major problems were noted with the proposed system of random sampling based on a predetermined truckload of material, the definition of the total concrete placed on the contract as a single lot, the initially proposed requirement for average entrained air content, and the present practice of accepting concrete on the basis of its having 85% of the required 28-day strength at 14 days.

After study of the findings, a revised proposal has been made for introducing such concepts into the Department's specifications for hydraulic cement concrete. The proposal is that a day's production of hydraulic cement concrete be considered a lot and that three samples per lot normally be taken for judging acceptability. The proper parameters for judging acceptance are based on a computerized statistical program (non-central-t) developed by the New Jersey Department of Transportation. These are discussed in the report and are recommended for adoption by the Virginia Department of Highways and Transportation.

Where conditions warrant, a larger number of samples per day may be required with consequent reductions in the risks of accepting poor concrete.

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INTRODUCTION

A pilot study was conducted to establish the feasibility of introducing statistical concepts into the testing and acceptance procedures for hydraulic cement concrete used by the Virginia Department of Highways and Transportation. The results, reported here, show that modification of the initially proposed revisions is desirable in order to establish the most workable procedure from the standpoint of existing restraints on the manpower available for inspection and testing. This report summarizes the data obtained in the study and includes new recommendations for the use of statistical concepts in the Department's standard specifications for hydraulic cement concrete.

The initial recommendations for use of statistical concepts were made after a study of the literature concerning the use of such procedures in judging the acceptability of hydraulic cement concrete. The report of that study summarized the problems involved and included the initial recommendations for revising the specifications for hydraulic cement concrete used by the Virginia Department of Highways & Transportation.(1)

PILOT STUDY

After a review of those recommendations by field construction and materials personnel, a pilot study was planned for the 1984 construction season. The scope and conditions of the study are outlined in a memorandum from W. E. Winfrey to the district engineers. This memorandum requested the district engineers to select suitable projects involving A4 bridge deck concrete and A3 structural and paving concrete for the

pilot study. Incidental concrete was excluded. The memorandum recognized that the testing and sampling performed for the pilot program could be used to satisfy both the existing and the proposed specifications. The current specifications were to govern the acceptance of concrete involved in the pilot study.

The Research Council's role in this study was as follows:

1. To develop guidelines for using the procedures to be adopted under the recommended changes in the specifications of the Virginia Department of Highways and Transportation.
2. To evaluate the effects of the proposed revisions in the specifications (Section 219) on inspection, sampling, and testing procedures.
3. To recommend modifications, if needed, to provide optimum coordination between state and contractor personnel for proper quality assurance in the production of hydraulic cement concrete.
4. To conduct workshops, as requested, to explain the new procedures to state, contractor, and concrete producer personnel.

Objectives 1 through 3 essentially have been accomplished, but because of significant modifications proposed under Objective 3, the workshops cited under Objective 4 are not appropriate until the final decisions have been made concerning the specification. Consequently, they will not be conducted as a part of this study.

Study Guidelines

The guidelines prepared to assist field personnel are included as Appendix A. These outline the major changes in acceptance procedures that would be made if the initially proposed specifications were adopted. Additional documents prepared by the Research Council are "Computation of Reduced Pay Factors" (Appendix B) and "Step-by-Step Procedures for Establishing Testing Schedule and Random Sampling of Hydraulic Cement Concrete" (Appendix C). These documents were furnished personnel involved in the pilot study for information and guidance and are included here for general information and as a part of the record for this study. However, the reader is cautioned that those documents are no longer applicable because of changes now proposed.

Participation

Five districts selected suitable projects for the pilot study and reported results. A total of 13 contracts were involved in these projects. In a number of cases additional data to provide information concerning potential effects of the changes were gathered. Summaries of the data submitted are shown in the following sections along with the special considerations and findings for each district.

PROBLEMS IDENTIFIED BY PILOT STUDY

The major problems identified by the pilot study are discussed below.

Random Sampling

Establishing random sampling on the basis of a specific truckload of material as originally required created a problem in that often only one person was assigned to a job and his multiple duties made it difficult for him to be available for sampling at the time a truckload arrived. This arrival time would be unknown and often unpredictable.

Definition of a Lot

From a statistical viewpoint, it was not realistic to consider a total contract as a single lot. A number of contracts run from early spring to late fall and conditions can change appreciably. This can result in apparently large standard deviations and consequently higher than necessary strengths to assure compliance with specifications.

Air Entrainment

The initially proposed reduction in the pay factor for low air content would apparently result in significant penalties for concretes now routinely accepted and apparently giving good service.

Ratio of 14-day to 28-day Strengths

While not a part of the pilot study, it was found that concrete accepted 14 days on the basis of 85% of the 28-day strength requirement did not always develop specification strengths in 28 days.

GENERAL SUMMARY OF TESTS AND FINDINGS BY DISTRICTS

The results of acceptance tests for strength and air content submitted by all the districts are given in Table 1. This table also includes the pay factors that would have been applied for strength and air entrainment under the initial proposal. The results for each district and the findings relating to any special tests that were made are discussed separately in the following sections.

Bristol

The Bristol District submitted data for four contracts using A3 concrete and two contracts for A4 concrete involving four ready-mix plants. All of the strength values submitted were well above minimum requirements and no reduction in pay for strength would have occurred. Under the initially proposed limits for average air content, three contracts would have had reductions in pay, but none would have had reduced factors under the modifications now being proposed. Comparative data for 14-day and 28-day strengths were not submitted by this district.

Culpeper

The Culpeper District supplied basic acceptance data for three projects as shown in Table 1. In addition, the district cooperated in making a number of special comparative studies as discussed in the following sections. Overall, all 28-day strengths were sufficiently high so that all pay factors for strength would have been 1.0 under the proposed specification. Average air contents were lower than required for 100% pay on the basis of the initial recommendation, but generally would be satisfactory if the suggested additional 0.5% deviation from the target value is allowed. These data, to be discussed later, show that the average strength at 14 days represents considerably greater than 85% of the average strength at 28 days. However, the 28-day strengths were satisfactory.

Table 1

Summary of Acceptance Tests Based on Proposed Statistical Procedures

Description	Type Concrete	n ^a	X, lbf/in ²	s, lbf/in ²	QL	PFS	n	A, Percent	PFA
<u>Bristol</u>									
Plant 107	A3	5	5,220	751	>99.9	1.00	25	4.92	0.83
110	A3	27	5,380	587	>99.9	1.00	67	5.86	1.00
127	A3	5	4,780	498	>99.9	1.00	27	5.90	1.00
130	A3	3	4,980	1,054 ^b	99.9 ^c	1.00	53	5.40	0.97
110	A4	6	6,080	582	99.7	1.00	24	6.00	1.00
130	A4	4	5,530	292	96.0 ^c	1.00	9	5.64	0.89
<u>Culpeper</u>									
Bridge Deck	A4	6	5,560	402	99.6	1.00	6	5.93	0.98
Substructure	A3	28	4,730	562	99.9	1.00	24	4.84	0.80
Retaining Wall	A3	4	4,520	541	99.5	1.00	7	5.71	1.00
<u>Fredericksburg</u>									
Pavement	A3	15	4,600	356	>99.9	1.00	15	5.86	1.00
<u>Lynchburg</u>									
Superstructure	A4	3	5,160	16	87.1 ^c	0.97	12	6.30	1.00
<u>Staunton</u>									
Bridge Deck (Normal)	A4	6	5,058	568	83.7	0.94	6	6.13	1.00
Bridge Deck (Lightweight) ^d	A4	29	5,310	430	76.5	0.86	27	6.44	1.00

^aThe symbols used in this table are defined as follows:

- n = number of tests made -- each test is an average of 3 determinations from a batch.
- X = average of tests made, lbf/in².
- s = estimated standard deviation from test data, lbf/in².
- QL = quality level -- percentage of all strength values in population above f'_c using σ of test results where $n > 5$ and 586 lbf/in² where $n < 5$. Normal distribution is assumed.
- A = air content
- PFS = pay factor for strength = $(QL + 10)/100$
- PFA = pay factor for air = $0.70 + 0.30 [X - X_{\min} - 1.0]$.

^bnot a valid estimate - concretes most likely constitute different mixtures.

^cbased on an assumed s of 586 lbf/in².

^dTwenty-eight day strength requirement was 4000 lbf/in².

Differences in Portion of Load Sampled

One of the concerns expressed by a representative of the Virginia Ready-Mixed Concrete Association with respect to the adoption of statistical acceptance techniques was the potential effect of testing errors on pay factors. Accordingly, it was properly pointed out that care was needed that sampling and testing be conducted strictly in accordance with specified test methods. The proposed specification continues the present practice of permitting sampling from a ready-mix truck after a minimum of 2 ft³ of concrete have been discharged rather than from the middle of the batch as required by the standard AASHTO method. To obtain information on the potential effect of this difference in procedure, four series of tests were made in the Culpeper District in which the beginning (after 2 ft³ discharged) and middle portions of the load were sampled. The strength results in lbf/in² were as follows:

a. Beginning	X	=	4,673
Middle	X	=	4,997
Difference		=	<u>324</u> (6.7% of average)
b. Beginning	X	=	5,970
Middle	X	=	5,237
Difference		=	<u>733</u> (13.0% of average)
c. Beginning	X	=	5,810
Middle	X	=	5,610
Difference		=	<u>200</u> (3.5% of average)
d. Beginning	X	=	6,010
Middle	X	=	5,330
Difference		=	<u>680</u> (12.0% of average)

In two cases the differences were not significant. In two cases the differences were over 10%, with the middle samples giving the lower result. Thus, it is concluded that testing and sampling differences are more likely to be the cause of variations than are any real differences in concrete strengths. Accordingly, sampling after 2 ft³ have been discharged is just as likely to produce a "representative" sample as sampling from the middle of the truck. It is noted that this procedure is now under consideration for adoption by ASTM and AASHTO.

Comparison of 14- and 28-day Strengths

Data were available to compare tests made for 28-day strengths with tests made for 14-day strengths on the same day but on different batches

of concrete. The results in lbf/in² were as follows:

July 3 - Avg. strength of 4 sets of cylinders at 28 days	= 5,827
Single set of cylinders at 14 days	= 4,073
Ratio	= 0.70
July 11 - Avg. strengths of 4 sets of cylinders at 28 days	= 5,156
Single set of cylinders at 14 days	= 4,957
Ratio	= 0.96
July 20 - Avg. strengths of 4 sets of cylinders at 28 days	= 5,690
Avg. of 2 sets of cylinders	= 5,670
Ratio	= 0.996

Since the 14-day and 28-day tests were made on different batches of concrete, the ratios computed do not represent true indications of strength gain by the same concrete. However, the variability obtained demonstrates the danger of projecting strengths at later ages on the basis of strengths at earlier ages when only a limited amount of data are available.

Variability in 28-day Strength Levels Based on Period Placed
(A3 Concrete in Substructure)

The concrete for one contract was placed over a period extending from August 8, 1984, through November 2, 1984. The total concrete placed was about 2,900 yd³. The overall average of the 28-day strengths of random samples was 4,730 lbf/in², with a standard deviation of 562 lbf/in².

An examination of these data on the basis of considering a day's production as a lot -- with the samples representing each day's production being averaged for a single value -- showed an overall average of 4,770 lbf/in² and a standard deviation of 599 lbf/in². This average is not significantly different from the average attained on the basis of

considering the total production as a single lot. It is noted, however, that the average of the strengths for the period from September 26 through November 2 was higher than that for the strengths from August 8 through September 21, the values being:

Aug. 8 - Sept. 21 average = 4,497, std. dev. = 397

Sept. 26 - Nov. 2 average = 5,158, std. dev. = 607

No explanation can be offered for this difference, other than possible differences in shipments of materials, stockpile conditions, or ambient conditions under which the test cylinders were prepared. The difference does point out, however, the danger of combining production over a long period of time as a single lot. If the true averages for different periods are different, the assumption of a single population will result in an estimated standard deviation greater than the true value for either population. In this case, however, all strengths were substantially higher than required by the proposed revision to the specification, so pay factors were not affected.

Analysis of 14-day Strength Results

For one project, normal sampling and testing at 14 days was conducted independently of the random samples tested at 28 days.

Thirty-three samples were taken from the production on 24 days between June 28 and November 9, 1984. The overall average of 14-day strengths for all samples was 4,450 lbf/in², with a standard deviation of 456. The average of production by days (all values for a given day averaged for a single value) was 4,480 lbf/in².

Sequentially plotting these results revealed three general levels of 14-day strengths for different periods as follows:

June 28 - Aug. 7 average = 4,047, std. dev. = 372

Aug. 8 - Sept. 21 average = 4,387, std. dev. = 328

Sept. 26 - Nov. 9 average = 4,903, std. dev. = 325

The ratios of average 14-day strengths to 28-day strengths for the periods from August 8 to September 21 and from September 26 to November 9 are of interest.

Aug. 8 - Sept. 21	Avg. 14-day strength	= 4,387
	Avg. 28-day strength	= 4,497
	Ratio S_{14}/S_{28}	= 0.98
Sept. 26 - Nov. 9	Avg. 14-day strength	= 4,903
	Avg. 28-day strength	= 5,158
	Ratio S_{14}/S_{28}	= 0.95

Fredericksburg

The widening of the concrete pavement on Interstate 95 afforded an opportunity to evaluate the feasibility of establishing a day's production as a lot and randomizing the selection of samples from sublots on the basis of one sample from each 1/3 of the workday. This system would be particularly advantageous where large volumes of concrete are placed. Sampling for these tests was independent of the normal acceptance testing, and test specimens were made by Research Council personnel. The randomizing procedure used is given in Appendix D.

Strength tests were made at 14 days and 28 days on specimens made at the same time from the same batch of concrete. These afforded a good basis of comparing the ratio of 14-day to 28-day strengths. The slopes of the log maturity-strength line based on the 14-day and 28-day values only were also determined and the results are given in Table 2.

The average of all 28-day strength results for the five lots was 4,595 lbf/in², with a pooled standard deviation of 356. Thus, all strengths were well above the minimum required level. The ratios of 14-day to 28-day strengths varied from 0.877 to 0.927, which indicates that in all cases the predicted strength on the basis of a 0.85 ratio would be high. The slopes of the log maturity-strength line based on the strength increase between 14 and 28 days varied from 1,189 to 1,710. However, since the slopes are based on only two points, no conclusions can be drawn concerning the significance of the variation.

Table 2

Strength Results for A3 Concretes Placed on I-95
in Fredericksburg District
(Based on randomly selected samples for statistical study)

Lot No.	Date Placed	Vol. Conc., yd ³	Air Content, %	Compressive Strength lb/in ² ^a		Strength Ratio, 14/28 days	Slope ^b
				14 days	28 days		
1	7/24	520	6.0	4,169	4,687	0.876	1,674
			5.6	4,478	5,049	.887	1,897
			6.8	4,269	4,687	.903	1,585
			Avg.	6.1	4,169	4,808	.889
2	7/26	516	6.5	4,265	4,783	.892	1,714
			2.0 ^c	4,426	4,969	.891	1,802
			5.5	4,253	4,744	.897	1,631
			Avg.	6.0 ^d	4,315	4,832	.893
3	8/01	177	6.7	3,684	4,121	.894	1,452
			6.0	3,458	3,869	.894	1,365
			6.3	3,299	3,909	.844	2,027
			Avg.	6.3	3,480	3,966	.877
4	8/02	950	5.2	4,429	4,890	.906	1,532
			5.6	4,293	4,690	.915	1,319
			5.4	4,134	4,611	.897	1,585
			Avg.	5.4	4,285	4,730	.906
5	8/07	392	5.3	4,889	5,154	.949	880
			5.1	4,651	5,207	.893	1,847
			6.1	3,684	3,922	.939	791
			Avg.	5.5	4,408	4,761	0.927

^aAverage of 3 tests.

^bSlope of log maturity vs. strength curve.

^cTwo determinations made. Both showed 2.0%.

^dLow result not included.

Exclusive of one very low result of 2.0% air, the average air contents for the five lots was 5.86%, which is above the required minimum. The one batch indicating a low air content probably resulted from a lack of air entrainment agent in the concrete. This deficiency was not detected by the normal quality control procedures. A variation of this degree must be judged to be the result of an operator error or equipment failure.

The results obtained in these tests indicated the feasibility of establishing one day's production as a lot with randomization of the time at which the sample would be obtained. This procedure would likely be particularly advantageous for the placement of pavement concrete.

Lynchburg

Data were provided for four sublots taken in accordance with the randomized procedure. These are shown in Table 1. Using the assumed standard deviation of 586 for these samples, since n was less than 5, gives a pay factor of 0.97. The standard deviation from the sample itself is extremely low and unrealistic. However, an assumed value as high as 515 would have resulted in an indication of full payment for this project. Data for comparison tests at 14-days were not available from this district. Under the modified statistical specification now proposed, the pay factor would be 1.00 for this project.

Staunton

Pilot studies were made for two bridge decks in the Staunton District, one using normal aggregates with a specification limit of 4,500 lbf/in² and the other using lightweight aggregate with a specification limit of 4,000 lbf/in². The results for the acceptance tests are shown in Table 1.

Results for Normal Weight Concrete

It is noted that the 14-day strength test results for the project with normal weight aggregate all exceeded 3,825 lbf/in², which is the criterion for acceptable strength based on 85% of the 28-day requirement. However, the ratios of 14-day to 28-day strengths for the 4 samples where such data were available varied from 0.900 to 0.904 and averaged 0.902. Thus, even though the 14-day tests indicated acceptable strengths, 1 of the 6 samples had less than 4,500 lbf/in² at 28 days, and on a statistical basis only 83.7% of the values exceeded 4,500 lbf/in². This would lead to a pay factor of 93.7% under the

initial proposal, but under the modified specification now proposed the pay factor would be 1.00.

Results for Lightweight Concrete

The same difficulty cited above was encountered with the bridge deck built with lightweight aggregate, with an appreciable failure to reach specification levels at 28 days.

Table 3 is a summary of the test results. As indicated, strength tests were made at both 14 days and 28 days. Using the customary criterion that the concrete is acceptable if 85% of the 28-day strength is reached in 14 days, all results of the 14-day tests were acceptable. A statistical analysis showed that the average 14-day value was 4,080 lbf/in², with a standard deviation of 310. Since 29 samples were tested, it can be concluded that these values represented a good estimate of the average and the standard deviation of the total population of test cylinders. Thus, these results indicate that, statistically, 98.5% of all 14-day strength values would be above 3,400 lbf/in².

A comparison of 14-day strengths to 28-day strengths showed very erratic strength gains from 14 to 28 days, and in a number of cases the 28-day strengths were lower than the 14-day strengths. The ratios of strengths at 14 days to strengths at 28 days shown in Table 3 varied from 0.82 to 1.15, the average being 0.95 with a standard deviation of 0.068. These values showed that for this lightweight concrete, the development of 85% of the required 28-day strength at 14 days did not assure that the 28-day strength would be reached. In fact, 7 of the 29 sets of cylinders tested at 28 days had average strengths of less than 4,000 lbf/in², the required minimum. The 28-day strengths averaged 4,310 lbf/in², with a standard deviation of 430. If it is assumed that the total bridge deck is a single lot, it is shown that statistically 23.5% of the values would be below 4,000 lbf/in². Under the initially proposed statistically based specification, the pay factor would be 0.865. The air contents averaged 6.44%, which indicated full compliance with the proposed specification for this characteristic.

A further analysis in the form of a control chart, to determine if low results could be isolated in terms of when the concrete was placed, revealed a significant trend. As shown in Figure 1, both the 14-day and 28-day results were relatively high and in the acceptable range at the beginning of the project, but significantly lower results were obtained as the work progressed so that the concrete placed on August 22 and August 28 had average 28-day strengths below the required 4,000 lbf/in². The average strengths of concrete placed on August 25 exceeded the 4,000 lbf/in² minimum limit by only a small margin. On August 30, average strengths were improved, and an upward trend was noted from then until the end of the project.

Table 3

Test Results -- Lightweight Bridge Deck
Staunton

Sample No.	Date Placed	w/c Ratio	Air Content %	Comp. Strength, lbf/in ²		Strength Ratio, 14/28 days
				14 days	28 days	
130	8/7	0.42	5.0	4,910	5,410	0.91
131		.41	6.0	4,560	4,910	0.93
132		.41	7.0	4,300	4,430	0.97
133	8/15	.41	6.0	4,380	4,810	0.91
134		.42	6.0	4,060	4,190	0.97
135		.41	-	4,280	4,190	1.02
136	8/18	.41	5.5	4,460	4,380	1.02
137		.41	6.0	3,950	4,480	0.88
138		.42	5.5	3,980	4,260	0.93
139	8/22	.42	7.0	3,750	3,970	0.95
140		.42	7.5	3,850	3,330	1.15
141		.42	7.5	3,950	4,230	0.93
142	8/25	.41	6.5	3,790	4,190	0.91
143		.42	6.0	3,640	4,460	0.82
144		.41	6.5	3,500	3,610	0.97
145	8/28	.42	7.5	4,110	3,690	1.12
146		.42	6.5	3,850	3,790	1.01
147	8/30	.42	6.5	3,650	3,950	0.92
148		.43	-	3,870	4,380	0.89
149	8/31	.42	7.5	3,820	4,080	0.94
150		.42	6.5	4,270	4,460	0.96
151		.42	6.5	3,800	3,960	0.96
152	9/5	.42	6.0	4,190	4,380	0.96
153		.42	6.5	4,260	4,430	0.96
154	9/7	.41	6.5	4,060	4,280	0.95
155		.41	6.5	4,240	4,500	0.94
156	9/8	.42	6.5	4,190	4,760	0.88
157		.42	7.0	4,230	4,720	0.90
158		0.42	6.0	4,340	4,910	0.88

NOTE: Average, lbf/in² = 4,080 4,315 0.95
 Std. Dev., lbf/in² = 310 434 0.068

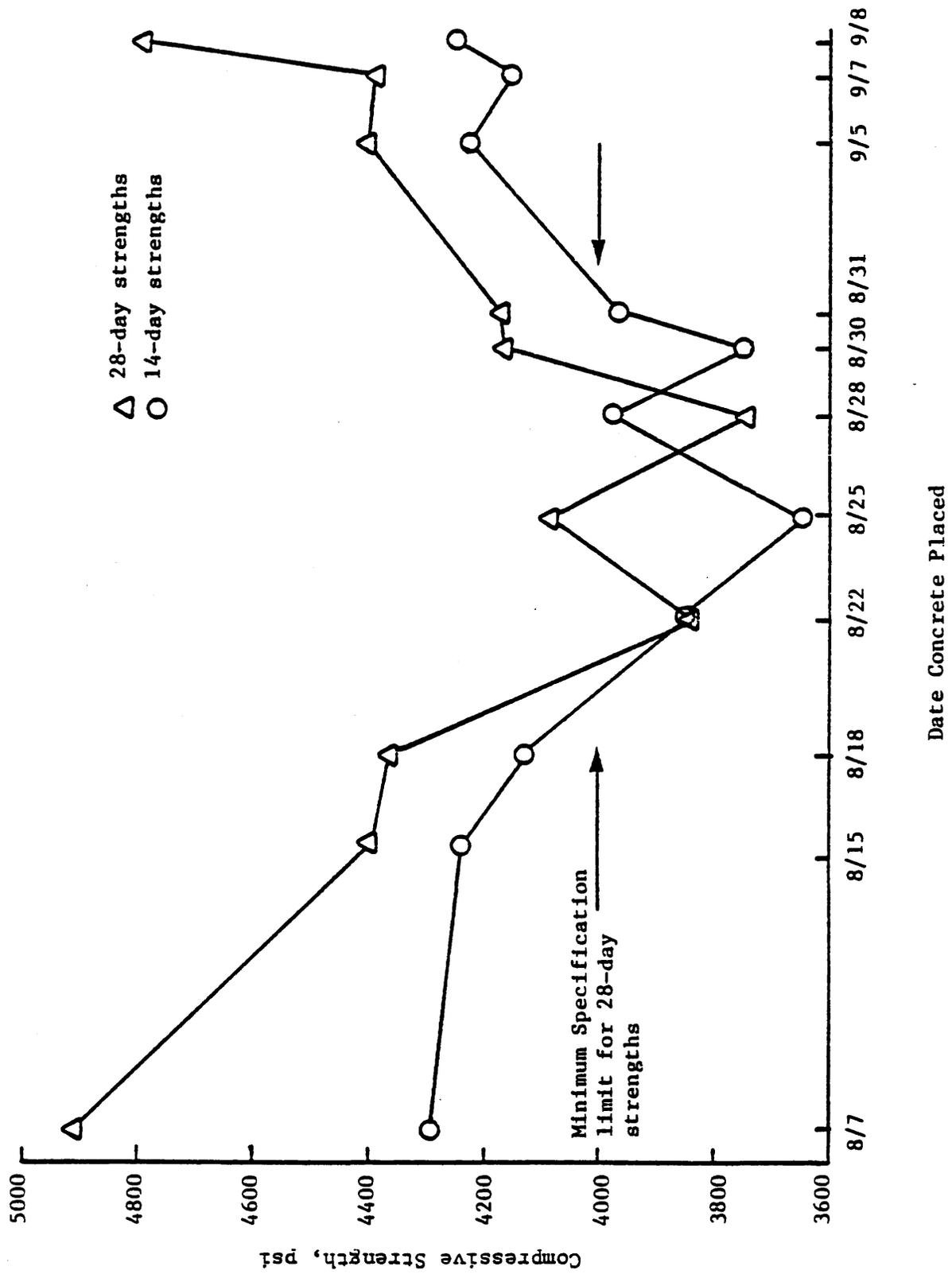


Figure 1. Average 14- and 28-day strength data for a day's production.

It is thus indicated that treatment of the total deck as a single lot is questionable from the statistical viewpoint. Thus, the results were analyzed on the basis of each day's production being a separate lot where at least 3 samples were available. Where only 2 samples were available for each day, two consecutive workdays were combined to form a lot. Results were then analyzed on the basis of the presently proposed revision to the specification. These are shown in Table 4. As indicated, on this basis, 98.4% of the bid price would be paid for this concrete.

Table 4

Lot Characteristics and Pay Factors
Lightweight Concrete Deck, Staunton District
(Based on Revised Statistical Specification, n = 3, except as noted)

Date Concrete Placed	Amount Concrete in Lot, Yd ³	Average 28-day Strength of Lot, lb/in ²	Std. Dev. of Lot, lb/in ²	Acceptable Average ^a (X_{ac}), lb/in ²	Pay Factor	Yd ³ Paid For
8/7	84	4,920	490	4,164	1.000	84.0
8/15	126	4,400	358	4,120	1.000	126.0
8/18	98	4,370	110	4,100	1.000	98.0
8/22	105	3,840	463	4,155	0.927	97.3
8/25	105 ^b	4,090	434	4,145	0.971	102.0
8/28 & 30	203 ^b	3,950	304	4,135	0.963	195.5
8/31	98	4,170	261	4,100	1.000	98.0
9/5 & 7	189 ^b	4,400	92	4,130	1.000	189.0
9/8	<u>98</u>	4,800	100	4,130	1.000	<u>98.0</u>
TOTAL	1,106					1,087.8

Percentage of Total Paid

98.4

^aAcceptable average:

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

f'_c = minimum class strength

k = acceptability constant (note)

s = standard deviation of sample, except 300 used when standard deviation is < 300

Note: When n = 3, k = .335

When n = 4, k = .444

When n = 5, k = .519

^b_n = 4

DISCUSSION OF RESULTS

Required Strength Levels

The strength results show that A3 concretes now being produced in compliance with the Virginia Department of Highways & Transportation specifications generally exceed the minimum requirements by a very wide margin. An examination of historical data shows that in the period from 1980 to 1984, 28-day strengths for A3 concretes placed by the Virginia Department of Highways and Transportation from all producers averaged about 4,700 lbf/in², with a standard deviation of 527 lbf/in². Thus, assuming a normal distribution, it is indicated that 95% of all A3 concretes placed ($X \pm 2 \sigma$) would be within the range from about 3,700 to 5,800 lbf/in². It is thus shown that the requirements for the minimum amount of portland cement rather than the strength specification controls the lower strength level. The same situation is not true for A4 concretes. Historical records show that the statewide average for A4 concretes over the past few years is about 5,200 lbf/in², with a standard deviation of 480 lbf/in², which is equivalent to a range from 4,200 to 6,200 lbf/in² for 95% of the values.

In keeping with the developing trend to use admixtures such as fly ash, slag, and silica fume as pozzolanic admixtures, and the need for concrete containing these materials to have the same levels of quality, it is believed that A3 requirements should be adjusted upwards so as to generally reflect the quality that is now being supplied to the Department. Historical and current data for A3 concretes indicate that a minimum design strength of 3,700 lbf/in² for A3 concretes would be suitable, as will be discussed more fully later. Concretes containing fly ash or slag would then be required to match existing production with concrete containing only portland cement. The 4,500 lbf/in² limit for A4 concretes should be retained.

Ratio of 14-day to 28-day Strengths

One significant finding revealed by the pilot study is the potential problem in the acceptance procedure of the Department whereby concrete is accepted when the 14-day strength is equal to or greater than 85% of the required 28-day strength. In the comparisons made during this project the ratio of 14-day to 28-day strengths often significantly exceeded 0.85, which creates the possibility that cylinders reaching the required 85% of 28-day strength in 14 days may not reach the required minimum 28-day strength. For all A3 concretes the 14-day strengths often equalled or exceeded the required 28-day strength, and no problem resulted with respect to compliance. However, in one of the five districts providing pilot study results, A4 concretes requiring a minimum 4,500 lbf/in² strength did not attain the required

strength, even though the strengths at 14 days were greater than 3,825 lbf/in² (.85 x 4,500). This same situation arose for a light-weight concrete with a requirement of 4,000 lbf/in². Problems would be further complicated by the proposed statistical specification, where the minimum requirement (f'_c) is interpreted as the value above which 90% of the distribution must fall.

In the other districts providing information, the ratio of strength at 14 days to strength at 28 days generally exceeded 0.85 when specimens were made from the same batch of concrete. However, because of the relatively high values of strengths at 14 days, all 28-day strengths were within specifications. Additional data are needed to determine if this is a problem with early acceptance in districts not participating in the pilot study.

It should be noted that under the principles of the maturity concept for strength development in concrete one should not expect a constant ratio of 14-day to 28-day strength. The ratio will vary according to the level of strength. In accordance with theory, the strengths of concrete made with the same materials and same water-cement ratios and air contents will be proportional to the logarithm of their maturities, where maturity is defined as the product of the curing temperature in degrees Fahrenheit and the time held at that particular temperature; that is, strength plotted against log maturity will be a straight line.

Thus, in the standard test strength will vary according to the time of aging since constant curing temperatures are used. The expected increase in strength between two periods of time would be an additive value related to the slope of the strength vs. log maturity line rather than a ratio of the strengths involved. However, in a study of tests for early acceptance of concrete it was shown that a precise straight line is not always attained when plotting strength vs. log maturity. (2) While the approximation may be sufficiently accurate for determining the general acceptability of concrete, it could not be relied on as a means for estimating the strength to which a reduced payment would be applied. In view of these indications and in order to avoid controversy, strength tests for acceptance should be made at the designated age until additional information is attained to establish relationships on the basis of the materials now being furnished to the Department.

PROPOSED MODIFICATIONS TO STATISTICAL SPECIFICATION

Lot Definition and Random Sampling

Appendix E provides the basic changes required in Section 219 of the 1982 edition of the Virginia Department of Highways and Transportation standard specifications for hydraulic cement concrete in order to incorporate the statistical concept. Revisions made independently since 1982 and having no relation to quality control and acceptance testing procedures are not indicated. With these changes, the section defines a lot as a day's production and establishes the normal frequency of testing at 3 samples per day. Randomization is based on the time the concrete is placed, with 1 sample being randomly selected for each one-third of the workday as described in Appendix D. Provision is made for adjustments when the inspector is not available at the exact time called for in the randomization schedule. Provision is also made for less than 3 samples when the production is substantially less than 300 yd³ for the day by combining consecutive days' productions into a single lot. This procedure equalizes the sampling problem for high production jobs and evens out the sampling and testing work load. While the lot size becomes a variable, it is believed that the variability of the results during a single day or consecutive production days is a more realistic basis for establishing acceptance strength levels than results covering a long period of time.

It is noted that where conditions warrant, a larger number of samples per lot (day's production) may be required with consequent reductions in the risks of accepting poor concrete.

Acceptable and Rejectable Average Strengths

Most applications of statistical procedures have established the acceptable quality level for strength of concrete as being an average strength such that not more than 10% of the values would normally fall below f' , the minimum class strength of the specification. This is the concept that is included in the previous recommendations. However, previously it was assumed that values associated with the normal distribution applied, even though the actual number of test values on a lot of concrete may have been smaller than desired to give good estimates of overall population averages and standard deviations.

The New Jersey Department of Transportation (NJDOT) has completed a study in cooperation with the United States Department of Transportation on statistical specification development, and the non-central-t program developed in that study is used to establish the applicable limits of the specification.(3)

This program establishes the percentage of the population that is defective on the basis of "Q" tables derived from a beta distribution. There is a different table for each value of n, the number of samples used for the average. "Q" in these tables is the counterpart of "z" when the normal distribution is used, although the mathematics for computing the various values is different. For a small number of samples this is recognized as being a better estimate of the true percent defective than is assuming that the sample average is equal to the population average and using the normal distribution table.

To compute the average of 3 test results needed that will indicate not more than 10% defective in the population at an assigned risk of rejecting acceptable material, the computer program developed by the NJDOT is utilized.

The required average is calculated from the equation

$$X = f'_c + ks, \quad (1)$$

where

X is the average of the test results,

f'_c is the minimum class strength,

k is the acceptability constant, and

s is the estimated standard deviation of the sample.

The value of k in this equation differs depending on the number of test results in the average and on the risk that material actually having an acceptable quality level will be rejected. It is determined using the computer program. In general terms, it is the minimum value of Q for a certain percent defective and risk.

When n equals 3 and a 5% risk ($\alpha = 0.05$) is allowed, k, computed from the non-central-t program, equals 0.335. Thus, the average of 3 tests required to assure that material which is truly 10% defective will not be rejected (or subjected to a reduced pay factor) more than 5% of the time is

$$X_{ac} = f'_c + .335s. \quad (2)$$

It is noted that, where conditions warrant, a requirement for a greater number of samples per lot can be established. In such cases the value of k increases, which in turn increases the acceptable average with an accompanying decrease in the risk of accepting poor material.

To apply reduced pay factors for concrete not fully meeting the requirement but not sufficiently deficient to warrant removal, it is necessary to establish an average of the 3 results that indicates a rejectable strength level (X_{rej}). By definition, concrete with average strength tests below X_{rej} would be subject to further tests and if allowed to remain in place would be paid for at a minimum pay factor. In the present proposal a minimum pay factor of 0.50 has been established and the rejectable average has been arbitrarily set at 1,000 lbf/in² below the acceptable average.

Table 5 shows the acceptable and rejectable averages that would be applicable under the proposed specification for A3 and A4 concretes with various standard deviations when n equals 3. When the estimated standard deviation is less than 300 lbf/in², the acceptable average would be calculated on the basis of a standard deviation of 300 lbf/in².

Table 5

Acceptable and Rejectable Averages for 3 Test Results for Various Standard Deviations

Standard Deviation	Class A3 Concrete		Class A4 Concrete	
	\bar{X}_{ac}	\bar{X}_{rej}	\bar{X}_{ac}	\bar{X}_{rej}
300	3,800	2,800	4,600	3,600
400	3,830	2,830	4,630	3,630
500	3,870	2,870	4,670	3,670
600	3,900	2,900	4,700	3,700
700	3,930	2,930	4,730	3,730
800	4,000	3,000	4,800	3,800

NOTE:

Class A₃

$$X_{ac} = f'_c \times ks \tag{3}$$

$$= 3,700 + (.335)s \tag{4}$$

$$X_{rej} = (f'_c - 1,000) + ks$$

$$= 2,700 + .335s$$

Class A₄

$$X_{ac} = 4,500 + .335s$$

$$X_{rej} = 3,500 + .335s$$

Pay Factor for Strength

There are several ways by which the amount paid for averages between the acceptable and rejectable can be determined. However, for simplicity, this amount is established on the basis of the amount by which the average of the test results is below the acceptable average. An accelerating scale to increase the reduction per unit of strength deficiency as the average decreases is used. Three zones are established as follows:

Zone 1	--	1 to 200 lbf/in ² below X_{ac}
		0.0002 reduction for each 1 lbf/in ² below X_{ac}
Zone 2	--	201 - 400 lbf/in ² below X_{ac}
		.04 + 0.0003 reduction for each 1 lbf/in ² greater than 200 below X_{ac}
Zone 3	--	401 - 1,000 lbf/in ² below X_{ac}
		.10 + 0.00067 reduction for each 1 lbf/in ² greater than 400 below X_{ac}

This schedule of reduction is shown graphically in Figure 2. It is empirically based on the general expectation that large deficiencies will result in greater proportionate damage than small deficiencies.

Table 6 shows the pay factors that would apply for various levels of strengths and standard deviations.

At first glance, Table 6 might be assumed to indicate that all A3 concrete will be accepted if the strength based on the total population averages 4,000 lbf/in² or greater and the standard deviation is less than 900 lbf/in². However, this is not true, since the average of the test results may not be the true average of the total population and the contractor is being given the benefit of the doubt when 4,000 lbf/in² concrete is accepted at full payment.

Table 7 shows the probability of acceptance for various levels of "true" percent defective. As indicated, if material at 10% defective is furnished, there is a .95 probability that it will be accepted, as was established by the value selected for k in designing the specification. However, note that if material with a true average of 4,000 lbf/in² and a standard deviation of 900 lbf/in² is supplied, the percent defective would be about 41%, which, as indicated in Table 7, would be acceptable by the average of 3 random samples only about 47% of the time. To meet this specification consistently without penalty, the concrete producer must proportion his ingredients to attain a true average (essentially equal to an average of 30 or more tests with the same materials) of about 4,300 lbf/in² for A3 concrete and 5,100 lbf/in² for A4 concrete. This computation assumes a standard deviation of 500 lbf/in².

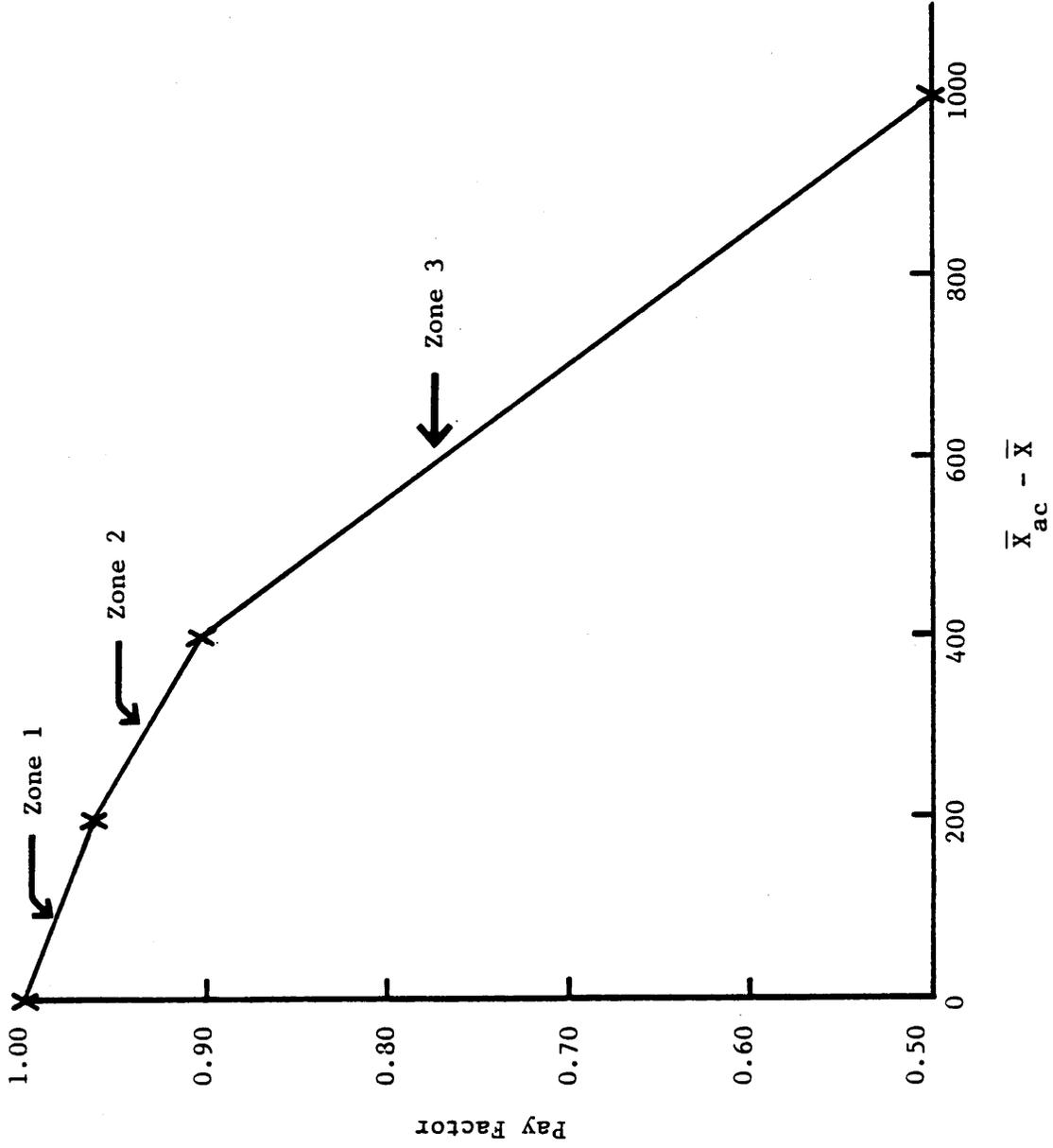


Figure 2. Reduced payment curve for various strength levels below \bar{X}_{ac} .

Table 6

Pay Factors for Various Standard Deviations and Strength Levels, A3 and A4 Concrete

Average 3 Tests		Standard Deviation						
A3	A4	300 (3800) ^a (4600) ^b	400 (3830) ^a (4630) ^b	500 (3870) ^a (4670) ^b	600 (3900) ^a (4700) ^b	700 (3930) ^a (4730) ^b	800 (3970) ^a (4770) ^b	900 (400) ^a (4800) ^b
2800	3600	0.500	0.500	0.500				
2900	3700	0.570	0.553	0.520	0.500	0.500	0.500	
3000	3800	0.640	0.623	0.590	0.570	0.553	0.520	0.500
3100	3900	0.705	0.687	0.660	0.640	0.623	0.590	0.570
3200	4000	0.770	0.755	0.728	0.705	0.687	0.660	0.640
3300	4100	0.837	0.822	0.790	0.770	0.755	0.728	0.705
3400	4200	0.900	0.885	0.860	0.837	0.822	0.790	0.770
3500	4300	0.930	0.923	0.910	0.900	0.885	0.860	0.837
3600	4400	0.960	0.952	0.939	0.930	0.923	0.910	0.900
3700	4500	0.980	0.974	0.966	0.960	0.952	0.939	0.930
3800	4600	1.000	0.994	0.986	0.980	0.974	0.966	0.960
3900	4700	1.000	1.000	1.000	1.000	0.994	0.986	0.980
4000	4800	1.000	1.000	1.000	1.000	1.000	1.000	1.000

(a) Numbers in parentheses indicate acceptable averages for A₃ concretes $f'_c = 3,700 \text{ lbf/in}^2$.

(b) Numbers in parentheses indicate acceptable averages for A₄ concretes, $f'_c = 4,500 \text{ lbf/in}^2$.

It is noted that the term "defective" as used here applies only in the statistical sense and is related to the levels set by the specification. It has no relation to defective material in the engineering sense. A material can be 100% defective in the statistical sense and still be satisfactory from an engineering viewpoint. The illustrations in Tables 5 and 6 are based on 3 samples per lot. However, equations 3 and 4 apply for any number of samples per lot greater than 3. It is necessary to determine the applicable k for each condition. Changes in both the number of samples tested, n, and the risk of rejecting good material, σ , change the value of k and consequently the acceptable and rejectable averages for the test results. Figure 2 and the schedule for reduction in payment for values below X_{ac} still apply when different acceptability constants, k, are used.

Table 7

Probability of Acceptance on Basis of Average of 3 Tests
When Producer Risk Is Set at 5%

<u>True Percent Defective</u>	<u>Probability of Acceptance</u>
5	0.988
6	.982
7	.975
8	.968
9	.959
10	.950
20	.819
30	.649
40	.471
50	.310
60	.179
70	.085
80	.028
90	0.004

Air Entrainment

With respect to air entrainment, a number of projects in the pilot study demonstrated that many contractors were not, in fact, using the center of the tolerance range as their target value, so the average of all air results often were more than 0.5% below the target, and under the initial proposal these would have been subject to reduced payment. However, in the absence of any indications that insufficient entrained air was being encountered, such a reduction in pay as previously suggested would not be justified. Accordingly, the required average before applying a reduced pay factor is now set at 5.0% for A3 concrete and 5.5% for A4 concrete. Only one project in the pilot study, a substructure having an air content of 4.84%, would be subject to reduced pay under the new proposal. Consideration might be given to waiving the requirement or allowing larger tolerance when the concrete involved would not be subject to damage from freezing and thawing. However, it is believed that should the now proposed additional tolerance be allowed in the specification, no problems would be encountered in obtaining full compliance in all cases.

RECOMMENDATIONS

1. The present practice of accepting concrete on the basis of the 14-day strength being 85% of the required 28-day strength should be discontinued. Concrete should be accepted at 14 days only if the 14-day average is equal to or greater than the 28-day requirement.
2. Statistical procedures provide a better evaluation of the quality of concrete being placed than do the presently used procedures and should be incorporated into the specifications. However, in lieu of the initial proposals based on combining all production in a contract as a single lot, a lot should be defined as a day's production. Samples randomized on the basis of the time the concrete is placed should be taken for each lot. For the normal situation, 3 samples should be taken for each lot, with one sample being taken during each one-third of the workday. If more than 3 samples are required per lot, 1 sample should be taken from each applicable time segment of the workday. The applicable time segment is the total workday divided by the number of samples to be taken.
3. The f' for A3 concrete should be increased from 3,000 lbf/in² to 3,700 lbf/in². This latter value will more closely define the strength of the concrete of this class supplied over the past 6 to 8 years as indicated by historical and current records.

Such an increase would not significantly affect the mixture proportions now being used for this class of concrete when portland cement is the only cementing ingredient. However, the higher value will establish a more suitable target for needed strengths where fly ash, slag, or other cementitious or pozzolanic materials are used in the concrete.

The value for f'_c for A4 bridge deck concrete should remain at 4,500 lbf/in².

4. Specification acceptance limits should be based on defining the desired average strength levels as being such that not more than 10% of the population of strength values are below the minimum design strength of the class of concrete involved (that is, not more than 10% is defective as defined statistically).

However, because of the uncertainties inherent in basing a decision on only a limited number of tests, acceptable averages for the test samples should be established on the basis of

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

where

X_{ac} is the acceptable average of the test results,

f'_c is the minimum design strength of the concrete specified,

k is the acceptability constant, and

s is the standard deviation of the sample.

The acceptability constant will be computed by the non-central-t program on the basis of an α error of 0.05, that is, there is not more than a 5% probability that material truly 10% defective would be rejected.

5. Reduced pay factors should be established for concrete not fully meeting the strength requirements but deemed not to be of sufficiently poor quality to justify removal and replacement. A rejectable average, X_{rej} , should be established at 1000 lbf/in² below the acceptable average. For test averages below X_{rej} , concrete would be subject to removal. If left in place, it should be paid for at one-half the bid price.

Concrete for which the average of test results is between the acceptable and rejectable averages should be paid for at a reduced pay factor based on the amount by which the test average falls below the acceptable average. A graduated scale as recommended in the report should be used.

ACKNOWLEDGEMENT

The authors gratefully acknowledge the assistance of Richard Weed and Ric Barros of the New Jersey Department of Transportation in interpreting the statistical significance of various approaches to judging the acceptability of concrete, and in the analysis of the operating characteristic curve of the limits now proposed in the specification.

1896

METRIC CONVERSION SHEET

SI CONVERSION FACTORS

To Convert From	To	Multiply By
Length:		
in-----	cm-----	2.54
in-----	m-----	0.025 4
ft-----	m-----	0.304 8
yd-----	m-----	0.914 4
mi-----	km-----	1 . 609 344
Area:		
in ² -----	cm ² -----	6.451 600 E+00
ft ² -----	m ² -----	9.290 304 E-02
yd ² -----	m ² -----	8.361 274 E-01
mi ² -----	Hectares-----	2.589 988 E+02
acre (a)-----	Hectares-----	4.046 856 E-01
Volume:		
oz-----	m ³ -----	2.957 353 E-05
pt-----	m ³ -----	4.731 765 E-04
qt-----	m ³ -----	9.463 529 E-04
gal-----	m ³ -----	3.785 412 E-03
in ³ -----	m ³ -----	1.638 706 E-05
ft ³ -----	m ³ -----	2.831 685 E-02
yd ³ -----	m ³ -----	7.645 549 E-01
Volume per Unit Time:	NOTE: 1m ³ = 1,000 L	
ft ³ /min-----	m ³ /sec-----	4.719 474 E-04
ft ³ /s-----	m ³ /sec-----	2.831 685 E-02
in ³ /min-----	m ³ /sec-----	2.731 177 E-07
yd ³ /min-----	m ³ /sec-----	1.274 258 E-02
gal/min-----	m ³ /sec-----	6.309 020 E-05
Mass:		
oz-----	kg-----	2.834 952 E-02
dwt-----	kg-----	1.555 174 E-03
lb-----	kg-----	4.535 924 E-01
ton (2000 lb)-----	kg-----	9.071 847 E+02
Mass per Unit Volume:		
lb/yd ³ -----	kg/m ³ -----	4.394 185 E+01
lb/in ³ -----	kg/m ³ -----	2.767 990 E+04
lb/ft ³ -----	kg/m ³ -----	1.601 846 E+01
lb/yd ³ -----	kg/m ³ -----	5.932 764 E-01
Velocity: (Includes Speed)		
ft/s-----	m/s-----	3.048 000 E-01
mi/h-----	m/s-----	4.470 400 E-01
knot-----	m/s-----	5.144 444 E-01
mi/h-----	km/h-----	1.609 344 E+00
Force Per Unit Area:		
lbf/in ² or psi-----	Pa-----	6.894 757 E+03
lbf/ft ² -----	Pa-----	4.788 026 E+01
Viscosity:		
cS-----	m ² /s-----	1.000 000 E-06
P ^c -----	Pa ^s -----	1.000 000 E-01

Temperature: °F-32) ⁵/9 = °C

1898

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1900

APPENDIX A

GUIDELINES FOR PILOT PROGRAM OF ACCEPTANCE TESTING FOR HYDRAULIC CEMENT CONCRETE BASED ON STATISTICAL PRINCIPLES

INTRODUCTION

These guidelines outline the major changes in inspection procedures, sampling, and testing required to implement the acceptance of concrete based on statistical principles as given in VHTRC Report No. 83-R36. During this pilot program, decisions concerning the acceptability of the concrete will be made on the basis of existing specifications and procedures and provisions for reduction in payment will not be enforced.

A final recommendation concerning the most workable and equitable system for reduced payments will be made on the basis of the findings of the pilot study.

INSPECTION PROCEDURES

All plant inspection procedures or changes instituted by the recent policy decision to remove state inspectors from ready-mix plants remain in effect. No change is needed for this pilot program.

FREQUENCY OF SAMPLING

The proposed specification basically establishes the size of a subplot for bridge decks at 50 yd³ and that for structural concrete at 100 yd³. Thus, the number of acceptance samples for each lot or each contract is determined by the total amount of concrete to be placed.

Generally each bridge deck is to be considered a lot for the purposes of final acceptance. Exceptions are for decks significantly greater than 1,000 yd³ or in special cases where there is a long time-difference in placing different portions of the deck. Exceptions may also occur when several small decks are being placed simultaneously or sequentially over a short period of time. In such cases, the engineer shall determine what portions of the work shall be considered as separate lots.

1902

RANDOMIZING PROCEDURES

A significant change has been made in the manner of selecting what truck load is to be sampled. Under the pilot program all samples must be selected by a suitable randomizing system. A recommended recognizing procedure is attached to this guideline, but other suitable procedures such as that outlined by ASTM D3665 are acceptable. While the particular randomizing method to use is a matter of convenience or judgement, it is emphasized that arbitrarily changing the load to be sampled on the basis of convenience must not be permitted.

The truck load to be sampled for acceptance tests for strength and air content for each subplot is to be based on the concrete placed in the job. Thus, should any truck load be rejected on the basis of improper slump, air content, temperature, etc. it is not counted for the purpose of determining the load to be sampled. The loads to be sampled shall be established prior to beginning the concrete placement. This information is kept confidential until the concrete arrives on the job.

START-UP AND MONITORING PROCEDURES

Start-up and monitoring procedures such as temperature, air content, slump, etc. are essentially the same under the pilot program as now in effect. An exception is that after the first three consecutive loads for bridge decks are found to be acceptable, random sampling for air content or slump or both at a rate of one such sample for each subsequent five loads of concrete may be substituted for 100% sampling and testing. However, 100% sampling will be reinstated for that particular property when a test result for any sample is outside the specification. In addition, concrete producers must be made aware that they must attempt to provide an average air content at or near the midpoint of the specification range. A requirement that the average for all A3 concrete must not be less than 5.5% and all A4 concrete must not be less than 6.0% will be introduced in the revised specification.

STRENGTH TESTS

All strength tests for acceptance will be made at 28 days using sets of 3 - 4" x 8" cylinders. All procedures for making, handling and curing test specimens remain the same.

Additional testing for strength at earlier ages is at the option of the District.

DATA REPORTING

Field personnel will continue to record all data on the same forms as now used and send reports to the Materials Division. In the event of low strength test results, acceptability will be determined using present procedures.

COMPUTATION OF PAY FACTORS

Reduced pay factors as proposed in the revised specifications will not be applied during the pilot program but will be computed on the basis of several criteria. The most workable and equitable procedure will be determined from the results of the pilot study.

ACCEPTABLE AVERAGE STRENGTHS

The major concept being introduced in the revised specification is that all the concrete in a lot, which will be in most cases an entire bridge deck or structure of significant portion of a structure, must have 90% of all strength values above the designated minimum for the class of concrete involved when judged by statistical procedures.

Under this concept the acceptable average of all strength results for the lot is always higher than the designated minimum for the class of concrete involved. How much higher is dependent on the standard deviation of the test results.

Since one of the questions to be decided is how to obtain the most suitable estimate of the standard deviation of strength results, all known variations in water/cement ratios should be recorded. Also any changes in sources of cement or aggregates must be known.

-1904

APPENDIX B
COMPUTATION OF REDUCED PAY FACTORS
FOR
REVISED SPECIFICATIONS FOR HYDRAULIC CEMENT CONCRETE
AS PROPOSED IN REPORT
"Improved Specifications for Hydraulic Cement Concrete"
(VHTRC 83-R36)

Distributed to: District Materials Engineers, VDH&T
Members, Concrete Research Advisory Committee

Virginia Highway & Transportation Research Council
Charlottesville, Virginia
August 1, 1984

1906

Computation of Reduced Pay Factors
FOR
Revised Specification for Hydraulic Cement Concrete
As Proposed in Report
"Improved Specifications for Hydraulic Cement Concrete"
(VHTRC 83-R36)

To promote understanding of the computation of pay factors in the proposed revisions of the concrete specifications, a review is presented here of the principles involved, the assumptions made, and the possibilities that the assumptions are not always true.

Principles Involved:

Under the proposed specification the acceptability of the entire lot of concrete (which in most cases is the total amount in a structure or bridge deck) is judged by both the overall average of the strength results and the amount of variation around that average is indicated by the standard deviation judged to be the most appropriate for the available data.

Schematically, the characteristics of the total population (all the concrete) is depicted as in Figure 1. In this figure,

f'_c = minimum design strength for class of concrete under test,

X = average strength of the concrete under test

Q = the number of standard deviations (or the fraction of a standard deviation) by which the average, X , exceeds the lower limits of the specifications, or in this case f'_c
(that is, $Q = (X - f'_c)/s$,

A_1 = the area under the curve for any given value of Q (determined from the normal distribution curve),

A_2 = 50% when dealing with a one-sided limit, and

A_3 = the area under the curve that is below f'_c for any given value of Q (always $50\% - A_1$).

Assumptions Made:

1. The test data have a normal distribution.
2. The average of the strength tests on the concrete cylinders is equal to the true strength of the concrete in place.
3. The estimate of standard deviation, s , (used in determining Q) is the true standard deviation of the population (all the concrete).

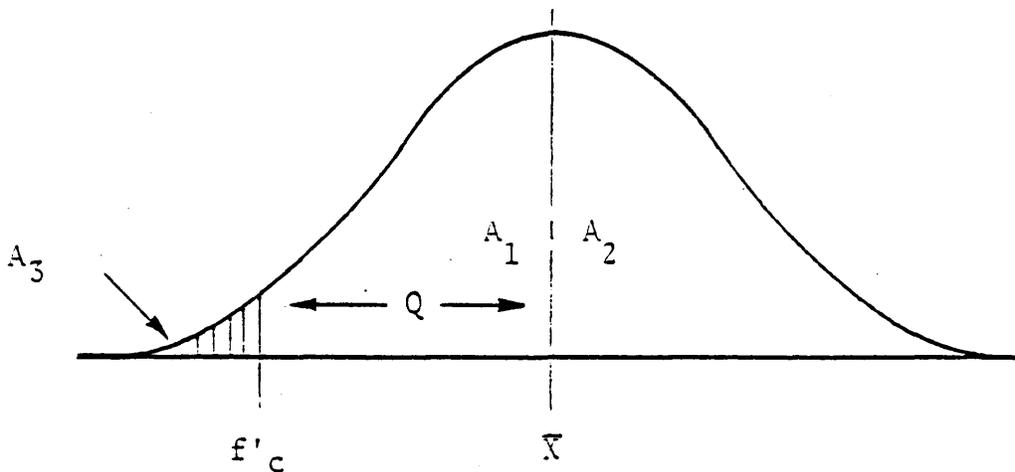


Figure 1. Significant parameters for statistical evaluation of concrete quality.

Risks Involved:

1. The average of the test results may not be a true indication of the overall average. For a small number of samples, normal testing variability might give an answer not quite the true value. When at least 30 test results are available, the risk that the test average is not correct is very small, but the risk increases as the number of tests decreases. Since making more tests is costly, the consequences of getting a wrong average for a few tests must be weighed against the cost of additional testing. Also, there is always a

1908

chance that something is wrong with the cylinders and that they don't properly indicate the strength of the concrete in place.

2. The standard deviation used may not represent the true standard deviation. If 30 or more test results are available in the same job, the standard deviation of the data is the best estimate of the true deviation. However, if less than 30 tests are available, a standard deviation based on experience may represent a more accurate value.

In the proposed specification a judgement was made that for 5 or fewer test results for a lot (or job) the standard deviation would be assumed. The value chosen is 586 lbf/in², which is based on the overall standard deviation for all concretes produced in the state over several years and is also consistent with expected values reported by others. When the number of tests is between 5 and 30, the sample standard deviation is used, except that a minimum value and a maximum value have been established for use in calculating the indicated quality level. That is, if the sample standard deviation is below 400 lbf/in², 400 lbf/in² is used in the computation of Q. Similarly if the sample standard deviation exceeds 800 lbf/in², 800 lbf/in² is used in the computation. These values represent good control and poor control as suggested by the American Concrete Institute (ACI). For large jobs or plants with high production volume the standard deviation of the most recent 30 test results provides the best estimate and will be used.

Concept of Quality Level

A judgement decision has been made, based on engineering experience and the work of ACI that concrete is fully acceptable when the quality level is 90% or higher. Referring to Figure 1, this means that A_3 , the percentage of values below f'_c must not exceed 10%. Correspondingly, A_2 equals 40% and $Q = 1.28$.

Another judgement decision has been made that if the quality level is lower than 60%, the concrete is unacceptable until cores have been taken from the concrete in place and a decision is made on the basis of the investigation conducted. Again referring to Figure 1, A_3 would be 40%, A_1 would equal 10% and Q would equal 0.253.

For concretes with a quality level between 60% and 90%, a reduced pay factor is applied. The reduction in the factor is directly proportional to the amount the quality level is below 90%. That is,

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

where:

PFS is the pay factor for strength, and

QL is the quality level.

For example:

If the QL is 85% then the pay factor is 0.95

$$[(85 + 10)/100].$$

In addition to a reduction in payment for low strengths it is also possible (although not probable) to have a further reduction for low average air contents. In this case the reduction is based on how much the average of all air contents falls below limits established at 0.5% below the target value in the specification, that is, 5.5% for A3 concrete and 6.0% for A4 concrete. If the air content is not more than 1% below the required average, the concrete is accepted at a reduced price, which is the minimum of 70% to which is added 30% multiplied by the proportion of the 1% above the acceptable minimum average air

1910

content. For example, if the required average is 5.5 and the results are 5.4, then the pay factor would be

$$0.70 + (5.4 - 4.5) \times 0.30$$

$$0.70 \text{ or } 0.9 \times 0.30 = 0.97$$

This may also be expressed as 97% of the unit price.

If a reduction occurs for both strength and air, the two factors are multiplied together for the final pay factor. The minimum overall pay factor being 0.5 (or 50%).

This overall pay factor, PFN, is then applied to the quantity of concrete involved in the contract or in the lot represented by the tests as the case may be.

Example:

As an example, assume 5 tests are made on a lot of A3 concrete and the average is 3,650 psi. Because of the low number of tests, a standard deviation of 586 psi is assumed. Also, assume that the air content tests made is 5.4%.

The quality level is then determined by first calculating Q, which is

$$\begin{aligned} Q &= X - f'_c / s \\ &= \frac{3,650 - 3,000}{586} = 1.09. \end{aligned}$$

From the distribution table the value for A_1 is read as 0.362.

Thus, the quality level, $A_1 + A_2$, is $0.362 + 0.50 = 0.86$, or 86%.

The pay factor for strength would then be $86\% + 10\% = 96\%$.

Since the average air content is 5.4% and the minimum average for air content without penalty is 5.5%, there would also be a reduction for an insufficient amount of entrained air.

$$\begin{aligned} \text{PFA} &= 0.70 + 0.30 (5.4 - 4.5) \\ &= 0.97 \end{aligned}$$

The overall pay factor then becomes

$$\begin{aligned}\text{PFN} &= \text{PFS} \times \text{PFA} \\ &= 0.96 \times 0.97 \\ &= 0.93 \text{ or } 93\%\end{aligned}$$

If the contractor has bid \$200 per cubic yard of concrete in place, and the total job represents 250 cubic yards, then the price reduction is:

$$\begin{aligned}\text{P.R.} &= 250 \times 200 \times (1 - 0.93) \\ &= 50,000 \times 0.07 \\ &= \$3,500.\end{aligned}$$

Another way to express the result is that the contractor would be paid 93% of his bid price for the amount of concrete.

NOTE: The numbers used in this illustration were arbitrarily selected and are not related to an expected situation for actual contracts.

-1912

APPENDIX C

STEP-BY-STEP PROCEDURES FOR ESTABLISHING TESTING SCHEDULE AND RANDOM SAMPLING OF HYDRAULIC CEMENT CONCRETE

by

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INTRODUCTION

The following step-by-step procedures for establishing the testing schedule for hydraulic cement concrete are provided as a guide for implementing the random selection of samples for determinations of both the compressive strength and air content of hydraulic cement concrete.

ACTIONS PRIOR TO START OF JOB

Step 1 -- Number of Sublots

Divide the total concrete in the job by the required sampling frequency.

Bridge deck -- 1 per 50 yd³

Structural -- 1 per 100 yd³

Round to next higher whole number

Example -- 740 yd of structural concrete

-- 740/100 = 7.4 rounded to 8 sublots

Step 2 -- Generate random numbers for selecting samples

Any statistically sound procedure may be used. If a hand calculator programmed to generate random numbers is available, this is the

1914

simplest procedure. ASTM Method D3665 is also suitable, as is the procedure for drawing numbered washers as described in Appendix E of the Research Council report VHTRC 83-R36.

If a 3-digit number is generated, use only the first 2 digits.

Generate one number for each subplot and list in the order obtained.

Step 3 -- Calculate the "Key" cubic yard for sampling

The 2-digit random number represents the percentage of the subplot used to compute the "Key" cubic yard.

Calculate by the equation

$$Y = (N-1)(F) + \frac{R(F)}{100},$$

where

Y = the "key" cubic yard,

N = the number of the subplot,

F = the frequency of sampling (cubic yards represented per sample), and

R = the random number assigned the subplot.

1915

Example -- For structural concrete where
N = 8 and F = 100.

$$R_1 = 32 \quad Y = 160(1-1) + \frac{32(100)}{100} = 32$$

$$R_2 = 74 \quad Y = 100(2-1) + \frac{74(100)}{100} = 174$$

$$R_3 = 16 \quad YY = 100(3-1) + \frac{16(100)}{100} = 216$$

$$R_4 = 23 \quad YY = 100(4-1) + \frac{23(100)}{100} = 323$$

$$R_5 = 2 \quad Y = 100(5-1) + \frac{2(100)}{100} = 402$$

$$R_6 = 64 \quad Y = 100(6-1) + \frac{64(100)}{100} = 564$$

$$R_7 = 83 \quad Y = 100(7-1) + \frac{83(100)}{100} = 683$$

$$R_8 = 41 \quad Y = 100(8-1) + \frac{41(100)}{100} = 741$$

1916

Step 4 -- Determine trucks to be sampled for compressive strength specimens, air content, and slump

When all trucks are of the same capacity,

Y/C rounded to next highest number is the truck number

Y is key cubic yd. from Step 3

C is capacity of truck

Example -- Assume truck capacity is 10 yd³

<u>Y</u>	<u>Truck Number</u>
32	4
174	18
216	22
323	33
402	41
564	57
683	69
741	75

NOTE: The truck numbers are based on the loads placed in the job, not the loads sent out from the plant. If a truck is rejected, it is not to be counted. Also, if all concrete is not delivered to the job in trucks of the same capacity, it will be necessary to determine the truck containing the key cubic yard by reference to production records showing how much concrete has been placed.

Step 5 -- Determine trucks to be sampled for air content test only

Air content is to be determined by the air pressure meter or volumetric method on all batches from which strength specimens are prepared. In addition, the revised specification permits randomized selection of 1 sample for each group of 5 after 3 consecutive satisfactory samples at the start of the job. Therefore, air content and slump are to be determined on the first batch each day, and if satisfactory, statistical sampling is resumed. Anytime a failure occurs, 100% sampling is resumed until 3 consecutive samples again meet the requirements. However, when an acceptance sample is to be taken within a group of 5, an additional sample for the determination of air only is not required. One random sample is taken for air content only for all other groups of 5.

Example -- In the schedule for strength tests, acceptance sampling is established for trucks 4, 18, 22, 33, 41, 57, 69, and 75.

The first 3 loads are tested: thus, subsequent groups of 5 are (4-8) (9-13) (14-18) (19-23) (24-29) (30-34) (35-39) (40-44) (45-49) (50-54) (55-59) (60-64) (65-69) (70-74).

Tests for air only are needed for groups (9-13) (24-29) (35-39) (45-49) (50-54) (60-64) (70-74). The simplest way to randomize the selection for the sample in each group is to place 5 numbered washers or numbered slips in a can or hat and draw out a number without looking.

Step 6 -- Record complete sampling schedule

Example

<u>Truck No.</u>	<u>Sampled</u>
4	Slump, Strength, Air
9*	Air
18	Slump, Strength, Air
22	Slump, Strength, Air
27*	Air
33	Slump, Strength, Air
37*	Air
41	Slump, Strength, Air
45*	Air
53*	Air
57	Slump, Strength, Air
61	Air
69	Slump, Strength, Air
72*	Air
75	Slump, Strength, Air

This schedule is to be kept confidential. The truck to be sampled should be announced to the contractor as it arrives on the job site.

*Assumed to be the truckload randomly selected from the group of 5.

Step 7 -- At start-up each day

Check temperature as needed.

Check air content and slump for all trucks delivered to job until 3 consecutive trucks show compliance for both air content and slump. Reject all noncomplying concrete. After 3 consecutive loads are in compliance, sample in accordance with predetermined schedule.

NOTE: Monitoring of air content may be done with Chace air indicator, but air pressure meter or volumetric method must be used for rejection of concrete. When a failing test for air or slump is obtained, testing of all loads should be resumed until 3 consecutive loads are again within specifications.

It is possible that one of the early trucks being monitored for air and slump will be scheduled for acceptance sampling and testing. If this occurs, the acceptance samples should be taken as required.

Step 8 -- Strength Testing

Make all compressive strength tests at 28 days. Each strength test is an average of results from three 4 x 8 in cylinders cast in plastic molds and tested with neoprene pads in steel-end caps.

Step 9 -- Reporting

Complete all data cards in accordance with existing requirements and send report to Materials Division.

In addition, the new specification requires that all abnormal behavior, or deviations from prescribed placement and curing procedures, be noted on the proper form and reported to the engineer.

NOTE: The schedule established for randomizing sampling is based on normal concrete production and placement procedures. When problems are encountered, sound engineering judgement must be used to solve them. In such cases, additional testing or testing at a different frequency is always permitted. However, deviations from the schedule and the reasons therefore should be recorded.

APPENDIX D

VTM-XX -- PROCEDURE FOR RANDOMLY SAMPLING HYDRAULIC CEMENT CONCRETE FOR ACCEPTANCE TESTS ON BASIS OF TIME

GENERAL

This procedure bases the selection of a truckload of concrete to be sampled on the time it is delivered to the job. A lot is defined as the concrete of a single class placed under the same contract during a single workday. Accordingly, the expected workday is divided into time-segments with each representing 1/n of the total period when n is the number of samples required for the lot. One sample is taken in each segment. The time for taking the sample is determined using a randomized procedure.

RANDOMIZING PROCEDURE

Determine the sampling time using the following step-by-step procedure.

Step 1. Establish Length of Sampling Period (SP)

- Expected time first load will be delivered to job..... _____
- Expected time last load will be delivered to job..... _____
- Expected duration of workday (min.)..... _____
- Estimated length of sampling period (1/n of workday, minutes) (SP)..... _____

Step 2. Select Random Numbers

From a table of random numbers or a hand calculator, select a group of 3-digit numbers equal to the number of samples to be taken and list these, following a decimal.

- R₁ = 0.
- R₂ = 0.
- R₃ = 0.
- R_n = 0.

1920

Step 3. Determine Sampling Time

$$\begin{aligned} T_1 &= \text{Starting Time} + R_1 \times (\text{SP}) &= \\ T_2 &= \text{Starting Time} + (\text{SP}) + R_2(\text{SP}) &= \\ T_3 &= \text{Starting Time} + 2(\text{SP}) + R_3(\text{SP}) &= \\ T_n &= \text{Starting Time} + [(n-1) (\text{SP})] + R_n (\text{SP}) &= \end{aligned}$$

Step 4. Action

Sample first load arriving on job after $T_1, T_2, T_3, \dots, T_n$.

PERMISSIBLE EXCEPTIONS

It is recognized that unexpected circumstances will at times alter the length of the workday so that sampling at the predetermined time may not always be feasible.

When a breakdown or delay occurs and it is expected that the work will continue until the planned amount of concrete is placed, the length of the delay should be added to the previously determined sampling time. When it appears that the day will be shortened and the day's work will be completed before the designated time of the final sample, the time should be recalculated on the basis of the expected shortened period, or where a shutdown is unexpected, the last load arriving could be sampled. The important criterion is that a set pattern or predictable time for sampling not be established. It is also possible that an inspector may not be able to sample the concrete at the preselected time because of other commitments. In such cases the first concrete load arriving on the job after he becomes available should be sampled.

1921

APPENDIX E

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

(Required to incorporate statistical concepts.)

"Road and Bridge Specifications"
Section 219

Based on June 1, 1982, edition. Changes made since 1982
and not related to statistical concepts are not indicated.

-1922

SECTION 219. HYDRAULIC CEMENT CONCRETE

Sec. 219.01 - 219.06 -- No change.

Sec. 219.07. Revise Table II-15 and footnotes to read as follows:

**TABLE II-15
REQUIREMENTS FOR HYDRAULIC CEMENT CONCRETE**

CLASS OF CONCRETE	Design Minimum Laboratory Compressive Strength at 28 Days ^a 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		Air Content percent
							Slump	Ball Penetration	
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	1/4 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	5' ± 1'
A3 General Use	3,700	57	1 in.	A	588	0.49	1-5	0-3	6±2
A3 Paving	3,700	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 Tread 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 a normal distribution, not more than 10 percent of the population of strength results will be below the indicated value. For approval, a mix design submitted in accordance with Section 219.07 should provide concrete strengths of at least 750 psi above the design minimum laboratory compressive strength based on the average of at least 3 independent sets of data utilizing the same materials.

** Aggregate size No. 7 shall be used in concrete posts, rails (not parapet walls) and other thin sections above the 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 6½ ± 1½ 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 - Same as present 219.12.

Sec. 219.09 - Same as present 219.13.

(Delete text of present sections 219.08 thru 219.11.
Adopt new sections 219.10 thru 219.19.)

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 Hydraulic Cement Concrete --

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

(1) Pavement, structural, and bridge deck 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 219.19. 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.

(4) Incidental concrete shall be accepted as described in 219.22.

(b) In addition to the prescribed procedures, the Department may reject any concrete which is obviously defective, or test any

1923

concrete and reject that which does not meet the requirement of these specifications.

Concrete which fails to meet any 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, 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: For the purposes of this specification a lot is a 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, water 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 on a deck in a single day shall be considered a 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 in that day may be considered as one lot and random sampling of sublots shall be conducted as in 219.14a3(a), 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 and Paving Concrete -- For volumes of concrete greater than 300 cubic yards, each day's production from the same mixer using the same materials shall be considered a lot. When the volume of concrete placed in a day is less than 300 cubic yards, the production on consecutive days may be combined to form a lot exceeding 300 yd³. A minimum of one sample shall be taken for any day's production.

(b) Inspection and Testing

1. Temperature: The Contractor is responsible for furnishing concrete within the temperature ranges established in Section 219.09. 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 219.09 will be rejected and removed from the job.

1925

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, the inspector shall note such observed deficiencies on Form TL-28 and shall immediately notify the Contractor's representative of his action and the notation made. In these cases, when so directed by the Engineer, additional inspection and tests on the hardened concrete will be made, and when deemed desirable the engineer may base the acceptance for strength of the concrete on the strength of the cores. The acceptable average shall be $f' + ks$, where k is the acceptability constant for the number of cores in the sample and an α risk of 0.05 percent determined by the non-central-t program. Where the 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).

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 shall be in accordance with AASHTO T-141, except that a sample may 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 also be outside the allowable range, 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 the 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 average of the recheck test and the original determination 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.

- (a) Acceptance Samples for Air Content and Compressive Strength: Samples for final acceptance based on air content and 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. A suitable randomizing procedure is described in VTM-XX. The portion secured for each test is to be taken after not less than 2 cubic feet have been discharged into

1927

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 may be obviously faulty. The appropriate acceptability constant, k, computed from the non-central-t program shall be used to establish the acceptable average (appropriate values for k when n = 3, 4, and 5 are given in section 219.15).

- (b) Final Acceptance Procedure: Final acceptance and the pay factor for bridge deck and structural concrete shall be in accordance with Sections 219.15 through 219.19. The requirements of these sections, in addition to the requirements in Section 321.22, also apply to pavement concrete.

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.

- (a) The lot shall be accepted at full bid price when the average is equal to or exceeds the acceptable average defined as follows:

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

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 class strength at 28 days, and

k the acceptability constant based on 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 as calculated from the test results, except that when the calculated standard deviation is less than 300 lbf/in², 300 lbf/in², shall be used.

-1928

(b) The rejectable average for a lot shall be $X_{ac} - 1,000$. When the average 28-day strength of the concrete is less than the rejectable average, X_{ac} , an investigation will be made to determine the cause of low strengths for the lot and, if deemed necessary, cores will be taken from the concrete in-place representing the lot.

Cores so taken will be used to judge the adequacy of the concrete in place. As indicated in ACI 318, if 85% or more of the design strength is achieved in cores, the concrete in place may be accepted as structurally adequate and the concrete may be allowed to remain in place with a pay factor of 0.50 of the bid price.

(c) When the average 28-day 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} determined in accordance with the following equations.

Zone 1(1 to 200 lbf/in² below X_{ac})

$$P.F. = 1 - [(X_{ac} - X_{test}) 0.0002]$$

Zone 2(201 - 400 lbf/in² below X_{ac})

$$P.F. = 1 - [0.04 + (X_{ac} - X_{test} - 200)0.0003]$$

Zone 3(greater than 400 lbf/in² below X_{ac})

$$P.F. = 1 - [0.10 + (X_{ac} - X_{test} - 400)0.00067],$$

where

P.F. = pay factor,

X_{ac} = the acceptable average as determined in Section 219.15, and

X_{test} = the average of the results of tests on the lot.

Sec. 219.16 Acceptance Criteria for Entrained Air Content

(a) Initial acceptance for placement: 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 on acceptance samples for entrained air in A3 and A4 concrete be above the following minimum limits.

1929

A3 concrete, general use: 5.0 percent
A4 concrete, posts and rails: 5.5 percent
A4 general use, bridge decks: 5.5 percent

- (b) When the average of tests for entrained air on acceptance samples is below the minimum specified in Section 219.16a but within 1.00 percentage point of that minimum, the concrete will be accepted at a reduced pay factor computed by the equation:

$$PFA = 0.50 + 0.50 [X - (X_{\min.} - 1.0)],$$

where:

PFA = pay factor for air,

X = average of test results on acceptance samples,
and

$X_{\min.}$ = minimum acceptable average for class of concrete involved.

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

- (c) 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, L, computed by ASTM Method C457, is 0.008 in or less, the concrete will be allowed to remain in place and a reduced pay factor for air of 0.50 shall be applied.

1930

Sec. 219.17 Combined Pay Factor for Acceptance --

In the event that the pay factors for any given lot 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 219.18 will be 0.50. Reduced pay factors, if applicable, shall apply only to the volume of concrete in those lots having less than required strengths or air contents.

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.)

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

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

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

where

T = total quantity of concrete in the item,

LS = lump sum bid price, and

other symbols are the same as in (a).

The total price reduction for the concrete shall be the sum of the price reductions for all lots.

Sec. 219.19 Pay Factors for Pavement Concrete --

1931

All appropriate requirements for concrete quality as previously defined in Section 219 shall apply. In addition, if a reduction in pay for insufficient thickness as described in Section 321 is warranted, the final pay factor for the concrete shall be the product of the indicated pay factors. That is,

$$FPN = PFN \times PFT,$$

where

FPN = final pay factor,

PFN = final pay factor for concrete quality as determined in Section 219.17, and

PFT = pay factor for concrete thickness as determined in Section 321.

Sec. 219.20 - Same as present 219.14.

Sec. 219.21 - Same as present 219.15.

Sec. 219.22 Incidental Concrete

Incidental concrete of less than 50 yd³ for any day's placement will be accepted on the basis of visual inspection and the concrete producer's certification that the required mix proportion of aggregate and cement have been used and that the maximum water/cement ratio has not been exceeded.

Placements greater than 50 yd³ but less than 300 yd³ will be accepted on the basis of visual inspection and the results of tests on a single set of cylinders. The concrete will be accepted if the average strength result is equal to or greater than f'_c , and rejected if the average strength is less than f'_c . If in the opinion of the Engineer the failing concrete will not critically affect the performance of subsequent portions of the project, the Contractor shall be given the option of removing the failing concrete and replacing it or leaving it in place and accepting a pay factor of 0.50 for the volume of concrete involved.

Placements greater than 300 yd³ in a single day shall be sampled, and tested for acceptance in accordance with the statistical procedures for structural concrete (Sections 219.13 - 219.19).

1932