Virginia Center for Transportation
INNOVATION
& RESEARCH

End-Result Specifications for Hydraulic Cement Concrete: Phase II

http://www.virginiadot.org/vtrc/main/online_reports/pdf/12-r2.pdf

CELIK OZYILDIRIM, Ph.D., P.E.
Principal Research Scientist

Final Report VCTIR 12-R2

VIRGINIA CENTER FOR TRANSPORTATION INNOVATION AND RESEARCH
530 Edgemont Road, Charlottesville, VA 22903-2454
www.VTRC.net

Standard Title Page - Report on Federally Funded Project

1. Report No.: FHWA/VCTIR 12-R2	2. Government Accession No.:	3. Recipient's Catalog No.:
4. Title and Subtitle: End-Result Specifications for Hydraulic Cement Concrete: Phase II		5. Report Date: August 2011 6. Performing Organization Code:
7. Author(s): Celik Ozyildirim, Ph.D., P.E.		8. Performing Organization Report No.: VCTIR 12-R2
9. Performing Organization and Address: Virginia Center for Transportation Innovation and Research 530 Edgemont Road Charlottesville, VA 22903		10. Work Unit No. (TRAIS): 11. Contract or Grant No.: 99203
12. Sponsoring Agencies' Name and Address: Virginia Department of Transportation 1401 E. Broad Street Richmond, VA 23219	Federal Highway Administration 400 North 8th Street, Room 750 Richmond, VA 23219-4825	13. Type of Report and Period Covered: Final 14. Sponsoring Agency Code:
15. Supplementary Notes:		

16. Abstract:

A study was undertaken to develop an end-result specification (ERS) for hydraulic cement concrete to be used by the Virginia Department of Transportation (VDOT) in transportation structures to obtain a uniform, consistent, quality product. The study was done in two phases. In the Phase I study, an ERS special provision was developed and applied to two pilot bridge projects, one each in two of VDOT's nine districts. In the current Phase II study, the ERS special provision developed in Phase I was updated and applied to more projects: of VDOT's nine districts, eight provided strength and permeability data for Class A3 concrete, eight provided strength data for Class A4 concrete, and seven provided permeability data for Class A4 concretes for bridge structures. Two paving projects were also included. The study addressed sampling, testing, quality characteristics, specification limits, bridge and paving concretes, and pay factors. VDOT's current specifications were applied for acceptance and rejection of all pilot projects, and pay adjustments were not applied.

VDOT's ERS has three parts. The first part covers process control measures. The contractor is responsible for the concrete design and is required to provide a quality control plan. The plan addresses all elements that affect quality, including mixture designs, aggregate sources, ingredients, tests and testing frequency, fresh and hardened concrete properties, and control charts. The second part covers the mixture design approval by VDOT. The third part covers project acceptance, which includes pay adjustments depending on the results of tests conducted under the first part.

In the current study, the first two parts of the ERS were well received and enabled innovations, minimized waste of materials, and provided green initiatives by reducing cement consumption. The third part dealing with pay adjustments had strong opposition from the industry and needs further evaluation. Thus, the study recommends that the first two parts of the ERS be implemented for use with bridge structures and the third part be deferred until more projects are evaluated. In addition, pilot projects for pavements should be initiated as was done for bridges.

A new, single class of concrete for both decks and substructures is planned for bridges that will provide the same high-quality concrete throughout the structure. This new class of concrete will enable more samples for ERS testing since there will not be more than one type of concrete in the structure. Projects with this new type of concrete should be included in further pilot tests of VDOT's ERS.

17 Key Words: End-result specification, concrete, quality index, pay factor, specification limit, permeability, strength, bridge, pavement		18. Distribution Statement: No restrictions. This document is available to the public through NTIS, Springfield, VA 22161.	
19. Security Classif. (of this report): Unclassified	20. Security Classif. (of this page): Unclassified	21. No. of Pages: 37	22. Price:

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

FINAL REPORT

END-RESULT SPECIFICATIONS FOR HYDRAULIC CEMENT CONCRETE: PHASE II

Celik Ozyildirim, Ph.D., P.E.
Principal Research Scientist

In Cooperation with the U.S. Department of Transportation
Federal Highway Administration

Virginia Center for Transportation Innovation and Research
(A partnership of the Virginia Department of Transportation
and the University of Virginia since 1948)

Charlottesville, Virginia

August 2011
VCTIR 12-R2

DISCLAIMER

The contents of this report reflect the views of the author, who is responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Virginia Department of Transportation, the Commonwealth Transportation Board, or the Federal Highway Administration. This report does not constitute a standard, specification, or regulation. Any inclusion of manufacturer names, trade names, or trademarks is for identification purposes only and is not to be considered an endorsement.

ABSTRACT

A study was undertaken to develop an end-result specification (ERS) for hydraulic cement concrete to be used by the Virginia Department of Transportation (VDOT) in transportation structures to obtain a uniform, consistent, quality product. The study was done in two phases. In the Phase I study, an ERS special provision was developed and applied to two pilot bridge projects, one each in two of VDOT's nine districts. In the current Phase II study, the ERS special provision developed in Phase I was updated and applied to more projects: of VDOT's nine districts, eight provided strength and permeability data for Class A3 concrete, eight provided strength data for Class A4 concrete, and seven provided permeability data for Class A4 concretes for bridge structures. Two paving projects were also included. The study addressed sampling, testing, quality characteristics, specification limits, bridge and paving concretes, and pay factors. VDOT's current specifications were applied for acceptance and rejection of all pilot projects, and pay adjustments were not applied.

VDOT's ERS has three parts. The first part covers process control measures. The contractor is responsible for the concrete design and is required to provide a quality control plan. The plan addresses all elements that affect quality, including mixture designs, aggregate sources, ingredients, tests and testing frequency, fresh and hardened concrete properties, and control charts. The second part covers the mixture design approval by VDOT. The third part covers project acceptance, which includes pay adjustments depending on the results of tests conducted under the first part.

In the current study, the first two parts of the ERS were well received and enabled innovations, minimized waste of materials, and provided green initiatives by reducing cement consumption. The third part dealing with pay adjustments had strong opposition from the industry and needs further evaluation. Thus, the study recommends that the first two parts of the ERS be implemented for use with bridge structures and the third part be deferred until more projects are evaluated. In addition, pilot projects for pavements should be initiated as was done for bridges.

A new, single class of concrete for both decks and substructures is planned for bridges that will provide the same high-quality concrete throughout the structure. This new class of concrete will enable more samples for ERS testing since there will not be more than one type of concrete in the structure. Projects with this new type of concrete should be included in further pilot tests of VDOT's ERS.

FINAL REPORT

END-RESULT SPECIFICATIONS FOR HYDRAULIC CEMENT CONCRETE: PHASE II

Celik Ozyildirim, Ph.D., P.E.
Principal Research Scientist

INTRODUCTION

The current Virginia Department of Transportation (VDOT) specifications for hydraulic cement concrete (HCC) are of the prescriptive type (VDOT, 2007). The minimum cementitious material and maximum water–cementitious material ratios (w/cm) are specified. The mixtures have a specified range of air content and slump, a maximum fresh concrete temperature, and a minimum design compressive strength at 28 days with standard curing. VDOT performs the tests required in the specifications. For pavements, flexural strength is also specified, but generally a correlation with compressive strength using job materials is established and acceptance is based on the compressive strength. Concretes with test results complying with the specification limits are paid for in full. The limits given in the specifications with regard to the minimum amount of cementitious material have discouraged innovation and have resulted in rich mixtures with high paste contents and a high degree of variability. Such mixtures are expensive and prone to volumetric changes because of shrinkage, high temperature generation during the hydration process, and chemical reactions leading to cracks. Aggregates used are generally gap-graded with intermediate sizes missing and have the potential for reduced stability, contributing to segregation.

If the strength requirement is not met, some contractors argue that the specification requirements were still met because (1) the concrete contained the specified amount of ingredients approved by VDOT; (2) the fresh concrete properties as tested by VDOT were satisfactory; and (3) the VDOT inspector was present during placement. Thus, the responsibility for producing a satisfactory product is not assumed by the contractor. Experience has shown that prescriptive specifications tend to obligate the agency to accept the completed work regardless of quality (Transportation Research Board, 2009). Therefore, there is a national interest in developing and using specifications where the contractor takes the authority and responsibility for the material produced (ACI Committee on Responsibility, 2005). Such specifications specify the performance characteristics of the end product. A commonly addressed type of specification that incorporates performance parameters and also includes elements of prescriptive specifications is the end-result specification (ERS).

In 1995, the Virginia Transportation Research Council (now the Virginia Center for Transportation Innovation and Research [VCTIR]) initiated a two-phase study on ERSs for concrete. In ERSs, performance parameters are specified and the design and proportioning of the mixtures are left to the contractor/producer. The study was undertaken to develop an ERS for HCC to be used by VDOT in transportation structures and pavements to obtain a uniform, consistent, quality product. In the Phase I study, a VDOT ERS special provision was developed and applied to two pilot bridge projects, one each in two VDOT districts, and the results were reported (Hughes and Ozyildirim, 2005). In the current Phase II study, the ERS special provision developed in Phase I was applied to pilot bridge projects in all nine VDOT districts, and the study is described in this report.

The Phase I study involved the following:

- the development of a VDOT special provision for ERS (an updated 2007 version used in Phase II is provided in Appendix A), which included specification language for structural and paving concrete

- the determination of appropriate specification limits for strength and permeability

- the selection of lot and sublot sizes

- the determination of a pay factor (PF) equation

- simulation of the special provision using actual field data for structural concrete

- application of the special provision for two pilot bridge projects (one in VDOT's Salem District and the other in VDOT's Culpeper District).

The objectives of the Phase I study were met, and the benefit of innovations was well demonstrated in the pilot project undertaken in the Salem District. In this pilot project, the mixture designed by the producer had ternary cementitious materials, which would not comply with VDOT's specifications at the time (VDOT, 1997) but did produce very-high-quality concrete under VDOT's ERS special provision. In the pilot project in the Culpeper District, the innovations of ERS were not employed and no changes to the VDOT's current specifications were made. Thus, there were no noticeable changes in the concrete properties obtained in this pilot project compared to other similar projects using current specifications.

PURPOSE AND SCOPE

During and after the Phase I study, questions were raised by the industry concerning sampling, testing, specification limits, and pay adjustments that needed further evaluation. In the Phase I study, only concrete related to bridge structures was included. Further, VDOT desired to expand the ERS pilot projects to other districts. Therefore, the current Phase II study was initiated.

The purpose of this Phase II study was to evaluate the prospects for using ERS for HCC. The study addressed sampling, testing, quality characteristics, specification limits, bridge and paving concretes, and PFs. VDOT's current specifications were applied for acceptance and rejection of all pilot projects, and pay adjustments were calculated but were not applied.

Concrete test data were collected for the bridge decks and substructures and pavements involved in the pilot projects. For bridge structures, eight of VDOT's nine districts (all except the Salem District) provided strength and permeability data for Class A3 concrete; eight (all except the Lynchburg District) provided strength data for Class A4 concrete; and seven districts (all except the Lynchburg and Culpeper districts) provided permeability data for Class A4 concretes. Two pavement projects from two districts, Lynchburg and Hampton Roads, were also included.

METHODOLOGY

Pilot projects from all nine VDOT districts were sought for bridge and pavement applications. The PF equation used in Phase I was as follows:

PF = 64 + 0.4 (Percent within limits [PWL]).

This equation allowed a maximum PF of 104%. Since the PF is applied to the in-place bid price, which is much higher than the concrete material cost, an incentive of 4% seemed inordinately high. Similarly, a penalty with the Phase I formula appeared to be too severe for the contractor. To reduce the impact of the initial PF, in Phase II, the formula was revised to the following:

PF = 82 + 0.2 (PWL).

Before the construction of the pilot projects, discussions or meetings were held with the ready-mixed concrete industry and contractors to explain VDOT's ERS, sampling and testing, and collection of the data. Trial batches were made before the construction of the structures in the pilot projects. During construction, contractors/producers tested the fresh concrete for air content, slump, density (unit weight), and concrete temperature. For the hardened concrete properties, VDOT tested the concretes for strength and permeability. Fresh concrete and hardened concrete data were collected and compiled by VDOT's Materials Division.

RESULTS AND DISCUSSION

This section summarizes VDOT's ERS developed in the Phase II study, data collected, innovations that occurred with the application of the ERS, and industry concerns.

VDOT's ERS Special Provision

The ERS special provision (see Appendix A) has three parts: (1) process control measures, (2) VDOT approval of mixture design, and (3) acceptance.

Process Control Measures

With regard to the process control measures, the contractor is required to provide a quality control (QC) plan. The plan addresses all elements that affect quality including mixture design, aggregate sources, ingredients, tests and testing frequency, fresh and hardened mixture properties, and control charts.

The contractor develops mixtures and selects proportions using specification materials and generates data on fresh and hardened concrete properties. The data can be historic data from the previous 12-month period using the same material sources or from trial batches. For historic data, guidelines in ACI 318 (American Concrete Institute [ACI], 2008) are specified where average results are sought that are above the specified minimum compressive strength (f 'c). For trial batches, at least three batches of concrete are required. The size of the trial batches has been an issue. At least three 3-yd^3 trial batches prepared at the plant are required, or if three small laboratory batches are prepared, at least one 3-yd^3 plant batch is required.

Among the quality characteristics used in Phase I were compressive strength, permeability, air content, thickness, cover depth over reinforcing steel, and pavement roughness. From the Phase I pilot projects it became apparent that obtaining measurements of the construction quality characteristics (i.e., thickness and cover depth over reinforcing steel) in a random manner presents difficult practical problems. Field personnel decided that the collection of these measurements is best done in a pre-selected grid pattern. However, pre-selection causes bias in the data and makes them unsuitable to use in a consistent statistical analysis. Thus, for Phase II, only the HCC material quality characteristics in the statistical procedures were used. This means the construction quality characteristics for delivery and placement remained as they are in VDOT’s current specifications (VDOT, 1997).

VDOT Approval of Mixture Design

The contractor submits information indicating that the mixture complies with the concrete properties specified in the ERS. The mixture design documentation includes a description and the amount of ingredients, w/cm, air content, slump, density, concrete temperature, permeability, and compressive strength data. VDOT reviews the information and if accepted, the mixture is used in the project. A few changes from VDOT’s current prescriptive specifications are important to note:

- There is no maximum w/cm or minimum cementitious material content.

- Combining cementitious material and aggregates, mixing gravel and crushed stone, and combining retarding admixtures and water-reducing admixtures are permissible.

- Curing boxes with continuously recording thermometers are specified since the boxes with “high-low” thermometers can lead to incorrect temperature information. Opening the lid of the box for a short period of time could lead to a high or low reading that would appear to indicate an invalid curing condition. Continuous temperature recording eliminates such anomalies.

- The slump and air content ranges can be selected based on the application rather than in accordance with VDOT's current specifications (VDOT, 2007).

Certain prescriptive requirements in VDOT's current specification are still applicable. For example, a minimum amount of pozzolans or slag is used to inhibit alkali-silica reactions and consolidating and curing procedures are still specified. A table giving Class F fly ash, slag, and silica fume proportions depending on the alkali content of cement is provided for convenience. However, the contractor can use proportions and specification material that are not in the table provided that standard tests are conducted to justify the new proportions.

Acceptance Sampling and Testing

Acceptance sampling depends on random sampling, which provides information on the entire project. A *lot* is a limited quantity of concrete manufactured for a specific application, such as a bridge deck or substructure. It contains uniform material in which all ingredients are the same and the proportions of aggregates and cementitious materials are within 5% of the design value. In Virginia, a lot is taken as the entire project except when it exceeds 500 yd^3 of concrete. This limit is to minimize the large pay adjustment since the pay adjustment is based on the lot size. The lots are divided into sublots. Each sublot has a maximum of 100 yd^3 of concrete or it is a day's production. All sublots are expected to be similar in size, and one sample is randomly selected from each sublot. If the day's production is known to be a small volume at the initial time random samples are selected, it can be added to the previous day's or subsequent day's concrete volume and a random sample must be selected for more than one day of concreting. If a day's production happens to be small during construction, tests for hardened concrete properties are not required. However, the engineer can require testing at any time. Those samples not based on random sampling will not be included in the statistical analysis. However, if the samples did not comply with the specifications, they would be rejected.

In ERS, the test methods and the acceptance criteria are given. Tests are conducted during prequalification and construction. The tests during prequalification can be more involved and time-consuming; however, those for jobsite acceptance should be easy and less costly. For example, the sulfate resistance test takes a long time to conduct and should be addressed during prequalification. The chloride ion penetrability test (Virginia Test Method 112) [VDOT, 2009] based on ASTM C 1202) is a more convenient test than the ponding test to indicate the permeability of concrete. Recently, an even more convenient test that measures the resistivity of concrete (Kessler et al., 2008) was introduced and is being evaluated by AASHTO. A task force has been formed, and round robin testing is ongoing. VCTIR is a member of the task force.

For sampling, the sample is secured after at least 2 ft^3 of concrete has been discharged from the truck or mixer as in the current VDOT specifications. This initial discharge is not used in the sample. This procedure has been used over the years, and VDOT continues to use it. This sampling permits comparisons with data previously collected in the same manner and permits immediate acceptance/rejection based on fresh concrete properties before any concrete is discharged into the forms. After casting, cylinders are kept in a curing box with a continuously recording thermometer. Acceptance tests consist of screening tests and PF tests (Ozyildirim, 2010, 2011). Independent assurance (IA) tests are also required.

Screening Tests

While the concrete is in the fresh state, the contractor conducts the screening tests for air content, slump, density, and temperature for every load. Where a large amount of concrete is used in a short period of time, the frequency of testing may be adjusted to avoid delays in the placement operation. If the results of the screening tests comply with the limits set, the load is used in the project.

Pay Factor Tests

PFs relate quality to actual pay. It is related to PWL (Ozyildirim, 2010). PWL is the percentage of the lot falling above a lower specification limit (LSL) for strength and below an upper specification limit (USL) for permeability. VDOT conducts the PF tests on hardened concrete.

Independent Assurance

From each sublot, VDOT takes a split sample of the fresh concrete. One half is tested by the contractor for the fresh concrete properties of air content, slump, density, and temperature. The other one half is used for IA tests of fresh concrete properties by VDOT. If the VDOT results are within the tolerances given in the applicable ASTM standards (ASTM, 2008; 2009a,b; 2010) the contractor's values are used even though the VDOT results may be outside (not meeting) the specification limits. IA is also applied to hardened concrete tests at a frequency of one sample per 1,000 yd^3 of concrete. For this purpose, concrete samples are obtained and tested by VDOT personnel that were not involved in acceptance testing.

Data Collected

Bridge Structures

Projects

The strength and permeability data for the bridge structure projects are presented in Appendix B. Some districts had more than one project. These projects used VDOT's ERS special provision, and data were collected on a random basis. The average value, maximum and minimum values, number of lots, specification limits, quality index range, PWL range and average, and PFs are given. In lots, generally five sublots are present. Sometimes, at the end of a project, a different number of sublots can be found if all sublots do not contain five units. During the collection of data, the amount of concrete for each sublot was not available in all cases. Therefore, it was assumed that all sublots were equal in size, and a weighted average considering the different number of sublots was also determined. The weighted average was calculated by summing the product of the average value with the number of sublots in each project and dividing by the sum of the sublots for all projects in a given class of concrete.

The A4 concrete has a specified compressive strength 1,000 psi higher than that of the A3 concrete; however, the difference obtained in the pilot projects given in Appendix B was 529 psi and the variability for the A4 concrete was higher than for the A3 concrete. The permeability values were low for both concretes.

Pay Factors

The PFs are summarized in Table 1. For permeability, concretes for structures in tidal water had lower permeability requirements; the USL was 1700 coulombs. Weighted averages for permeability included all elements, then elements in tidal areas (USL 1700 coulombs), and then elements not in tidal waters (USL 3200 coulombs for A3 concrete and 2200 coulombs for A4 concrete). The results in Table 1 indicate that based on the weighted average for compressive strength, there would be a bonus of 0.42% for A3 concretes but a penalty of 1.96% for A4 concretes. For permeability considering all elements, there would be bonuses of 1.73% for A3 concretes and 1.18% for A4 concretes. Permeability data summarized in Table 1 indicate penalties for A4 concretes: this was due to one project having very high permeability, as shown in Appendix B, and other projects receiving a bonus for permeability.

The pilot project with the most sublots (161) of A4 concrete was in the Richmond District, as shown in Appendix B. In that project, the PF was 94.90%, a 5.1% penalty if the ERS pay adjustment had been enforced. The project had 32 lots since the maximum lot size was taken as 500 yd^3 of concrete and the maximum sublot size was taken as 100 yd^3 of concrete. This penalty initiated critical reviews of the ERS by the industry especially since the average value of the 161 sublots was 4,820 psi, 820 psi above the minimum specified strength of 4,000 psi for the A4 concrete. However, a closer look indicated that the compressive strengths ranged from 3,270 psi to 6,350 psi. Twenty sublots, 12.5%, had values below 4,000 psi; in the current VDOT specifications, these values would not comply with the strength requirement. Thus, a penalty for the concrete would be incurred under both VDOT's ERS and VDOT's current specifications. The penalty in the current VDOT *Manual of Instructions* (VDOT, 2009) is given as a 1% price reduction per percent below the design minimum compressive strength. Thus, the

Table 1. Pay Factors for Bridge Concretes

Class	Property	Pay Factor Based on	Mean	Std. Dev.	Max.	Min.	n Sublots	Pay Factor (%)
A3	Strength (psi)	Average	4647	573	5945	3601	274	99.72
		Wt. avg.	4759				274	100.42
	Perm. (coulombs)	Average	1340	437	2267	640		101.05
		Wt. avg. all	919				246	101.73
		Wt. avg. (USL 1700)	459				128	102.00
		Wt. avg. (USL 3200)	1419				118	101.45
A4	Strength (psi)	Average	5624	740	6974	4360	397	98.91
		Wt. avg.	5288					98.04
	Perm. (coulombs)	Average	1090	245	1609	707	336	100.44
		Wt. avg. all	688				336	101.18
		Wt. avg . (USL 1700)	433				217	102.00
		Wt. avg. (USL 2200)	1155				119	99.69

n = number of sublots; Perm. = permeability; wt. avg. = weighted average; USL = upper specification limit.

penalty for the 20 sublots would be 6.35%. However, some of these concretes had strengths below 90% of the design strength, indicating the need for further investigation and possibly further price adjustments or corrective actions.

This project also indicated the need for more QC and reduced variability since satisfactory average strengths do not relate to satisfactory values for the total project. For example, compressive strength data for A4 concrete for one of the districts (see Appendix B) showed an average of 5,080 psi with a standard deviation of 860 psi, leading to a penalty, whereas in another project with an average compressive strength of 5,010 psi and a standard deviation of 300 psi, a bonus was indicated. In ERSs, variability is considered for pay adjustment with the goal of obtaining a uniform, consistent product that would ensure quality concrete for the total project.

Pavement

Projects

Two pavement projects, Madison Heights Bypass and Battlefield Boulevard, were included to evaluate possible PFs. These projects did not include VDOT's ERS special provision but were simply available projects on which data could be collected and evaluated using ERS as a shadow specification.

Madison Heights Bypass (US 29): Lynchburg District. The Madison Heights Bypass redirects traffic away from downtown Lynchburg and Madison Heights on Route 29. The bypass was built using continuously reinforced concrete pavement (CRCP), which was awarded in two contracts and constructed in two sections by two separate contractors. The first section, starting at US 460, was about 5 miles long and was built in the summer of 2004. The second section was almost 6 miles long and was built during the summer of 2005 (Ozyildirim, 2007). The data on fresh concrete properties were collected every hour, and strength and permeability tests were conducted with random samples for each sublot, which was 0.2 lane-mile.

The mixture proportions for the second section are given in Table 2. The coarse aggregate was No. 57 crushed aplite with a nominal maximum aggregate size of 1 in. The fine aggregate was natural sand. The design w/cm was 0.49, but the w/cm actually averaged 0.46. Project specifications required that the concrete have a minimum flexural strength of 650 psi at

Table 2. Mixture Proportions for Pavement Projects (lb/yd^3)

Materials	Madison Heights Bypass, Section 2 (Lynchburg District)	Battlefield Blvd. (Hampton Roads District)
Cement	443	282
Fly ash	148	---
Slag	---	282
Water	290	254
Coarse aggregate	1657	1883
Fine aggregate	1224	1222
Design w/cm	0.49	0.45

w/cm = water–cementitious material ratio.

28 days. For convenience and reduced variability (flexural strength exhibits higher variability than compressive strength), acceptance was based on compressive strength once a correlation between compressive and flexural strength was derived. Based on the correlation, a value of 4,000 psi was selected to yield a flexural strength of 650 psi (Ozyildirim, 2007).

Battlefield Boulevard: Hampton Roads District. The I-64 / Battlefield Boulevard Interchange Project in the City of Chesapeake included 1 mile of CRCP with five lanes in each direction. Traffic was moved to the outside lanes, allowing for construction to take place in the center lanes. An on-site batch plant provided the concrete, uninterrupted by traffic.   The mixture proportions are given in Table 2. The coarse aggregate was No. 57 crushed traprock with a nominal maximum aggregate size of 1 in. The fine aggregate was natural sand. The contractor chose to use flexural strength for acceptance instead of correlating flexural strength to compressive strength and basing acceptance on compressive strength.

Pay Factors

The PFs for the pavement projects are summarized in Table 3. Different specification limits were tried. In bridge decks, the LSL for the compressive strength of substructure concrete is 3,800 psi. Based on that, the PF would be 100.38% for the Lynchburg District project and 102% for the Hampton Roads District project, both indicating a bonus. However, for an LSL of 4,500 psi, the PFs would be 90.53% and 99.96%, indicating a penalty. Permeability values for the Lynchburg District project were based on 1700 coulombs, which is the value used for bridge decks over tidal water and indicates a PF of 102%. The Battlefield Boulevard pavement had flexural strength values. The minimum flexural design strength was 650 psi. The LSL at the design strength would have a PF of 100.40%. However, it is more appropriate to have the LSL above the minimum design strength. If LSL were chosen as 680 psi, the PF would be 99.86%.

Innovations with ERS

This section discusses examples of the pilot projects that showed the innovations possible with the ERS.

Aggregate and Admixture Selection

A project on Route 624 over the Cat Point Creek in the Fredericksburg District has 10 spans, each 81.5 ft long. In the deck, a combination of crushed stone and gravel was used. The mixture contained retarding admixture and water-reducing admixture. Such combinations are not allowed in VDOT's current specifications unless requested by the contractor and approved by the project engineer. Satisfactory results were obtained.

Combined Aggregates

For the project on Route 5 over the Chickahominy River in the Richmond District, the gravel coarse aggregate available to the contractor did not comply with the VDOT specifications for ASTM No. 57 grading (VDOT, 2007). It had a low amount of aggregate, 7.5%, passing the

Table 3. Data and Pay Factors for Pavement Projects

District	Property	Mean	Std. Dev.	Max.	Min.	n	LSL	Q Range	PWL Range	Avg. PWL	Avg. PF (%)
Lynchburg	Compressive strength (psi)	4431	339	4910	3880	26	3400	0.95 to 9.76	82.14 to 100	98.4	101.68
							3800	0.18 to6.91	56.39 to100	91.9	100.38
							4000	-0.23to 5.49	41.84 to 100	84.9	98.98
							4500	-1.69 to 1.98	0 to 100	42.66	90.53
	Property	**Mean**	**Std. Dev.**	**Max.**	**Min.**	**n**	**USL**	**Q Range**	**PWL Range**	**Avg. PWL**	**Avg. PF**
	Permeability (coulombs)	1236	235	1252	1217	26	3200	7.57 to 10.28	100 to 100	100	102.00
							1700	1.74 to 2.50	100 to 100	100	102.00
							1500	0.97 to 1.47	82.74 to 95.61	87.52	99.50
Hampton Roads	**Property**	**Mean**	**Std. Dev.**	**Max.**	**Min.**	**n**	**LSL**	**Q Range**	**PWL Range**	**Avg. PWL**	**Avg. PF**
	Compressive strength (psi)	5119	406	5770	4330	2	3800	2.41 to 4.34	100 to 100	100	102.00
							4000	1.98 to 3.77	100 to 100	100	102.00
							4500	0.89 to 2.35	79.67 to 100	89.84	99.96
	Property	**Mean**	**Std. Dev.**	**Max.**	**Min.**	**n**	**LSL**	**Q Range**	**PWL Range**	**Avg. PWL**	**Avg. PF**
	Flexural strength (psi)	864	162	1096	630	2	650	1.02 to 1.76	84 to 100	92	100.40
							680	0.86 to 1.54	78.67 to 100	89.34	99.86
							700	0.76 to 1.38	75.33 to 96	85.66	99.14

n = number of sublots; LSL = lower specification limit; Q = quality index; PWL = percent within limits; PF = pay factor, USL = upper specification limits.

½ in sieve. The ERS allowed the contractor to blend the noncompliant aggregate with No. 78 gravel to yield an acceptable grading, as indicated in Figure 1. The gravel pit was located close to the concrete plant, which allowed the contractor to save considerable money in shipping costs.

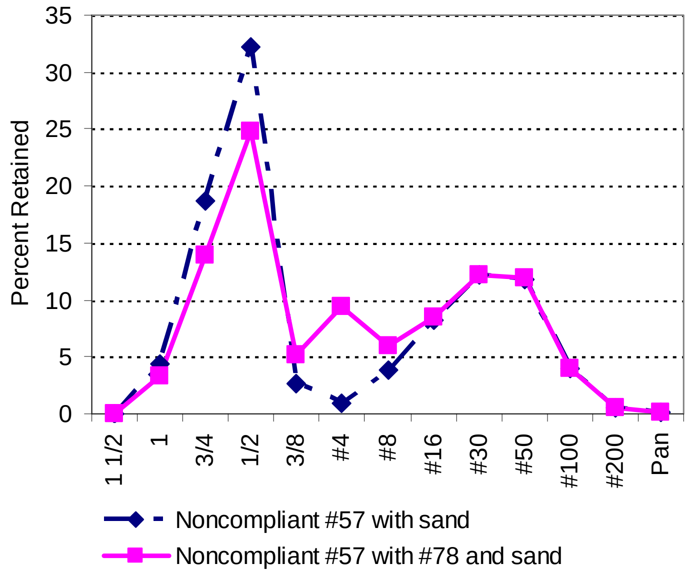

Figure 1. Combined Aggregates for Route 5 Bridge

Curing Boxes

For the I-95 widening project in the Northern Virginia District, curing boxes with continuously recording thermometers were used. This was to ensure that the initial curing temperature complied with the applicable ASTM requirements (ASTM, 2009c). The specimens were transported to the laboratory for moist-curing. Figure 2 shows a typical temperature data

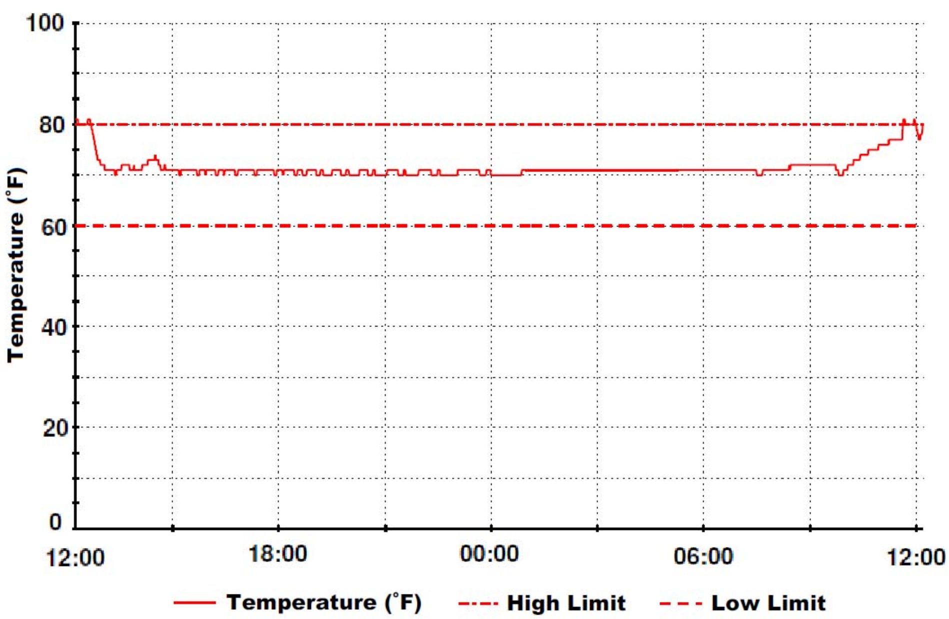

Figure 2. Temperature of Curing Box in First 24 Hours After Concrete Preparation

chart. In the past, high and low thermometers were used and if a spike occurred, the cylinder test results would not be valid. With the continuous recording thermometers, the severity of the temperature extremes can be seen and corresponding action can be taken. If the spike occurs only for a short period because of the opening of the lid of the box, the cylinder would be acceptable for testing. For extended periods of curing at a nonconforming temperature, the concrete samples would not be acceptable and corrective actions, including the replacement of the box or the heating or cooling element, would be taken.

Mixture Proportions

For the Chincoteague Bridge project in the Hampton Roads District, the bascule pier footing was 83.5 ft by 51 ft by 7 ft deep. In such mass concrete applications, management of the temperature rise is needed to control cracking. The mass concrete special provision (VDOT, 2004) requires a maximum temperature of 160ºF and a maximum temperature differential of 35ºF within the element unless an analysis is submitted demonstrating that the element is sufficiently reinforced to prevent crack widths in excess of those listed on the plan. The temperature is measured at the centroid of the footing or wherever the maximum temperature is anticipated and at the elevation of the bottom mat and top mat of reinforcing steel vertically in line with the location of the maximum temperature. The specified concrete was A3 concrete, which has a minimum 28-day compressive strength of 3,000 psi and a minimum cementitious content of 588 lb/yd^3. To control the temperature rise and cracking, a low total cementitious material content of 539 lb/yd^3 including a 30% Class F fly ash was used. The mass concrete placement was successfully completed. The specification limits for maximum temperature and temperature differential were met. There were no visible cracks, and strengths exceeding 4,000 psi were obtained.

Control Charts

With the ERS, control charts for fresh and hardened concrete properties showing the interaction between the different parameters are prepared. Organizing data enables immediate changes. The charts are for air content, slump, density, and temperature for the fresh concrete properties and for strength and permeability, including moving average of three, for the hardened concrete properties. The hardened concrete specimens were tested at 28 days. Strength tests at 7 days are being considered to determine if these results would indicate potential problems at an earlier age.

In a pilot project in the Northern Virginia District, the results of the air content and density tests clearly indicated a problem. A high air content is expected to indicate a low density, and vice versa. However, in this project, this relationship was not apparent, as shown in the control charts for air content and density in Figure 3. Such early anomalies would indicate a potential problem with the concrete, the equipment, or the testing procedure. This anomaly was brought to the attention of the inspector; in such cases, recalibrating or replacing the equipment, repeating the testing, and casting samples for hardened concrete tests are recommended. When a similar anomaly occurred the second time, two cylinders were prepared for evaluation. The air content of this normal weight concrete was reported as 5.2%, and the fresh density as 124.5 lb/ft^3. The density of the cylinders at the hardened state was 152.7 lb/ft^3 and 152.3 lb/ft^3, respectively, indicating that the low density reported at the fresh state was due to the measuring error.

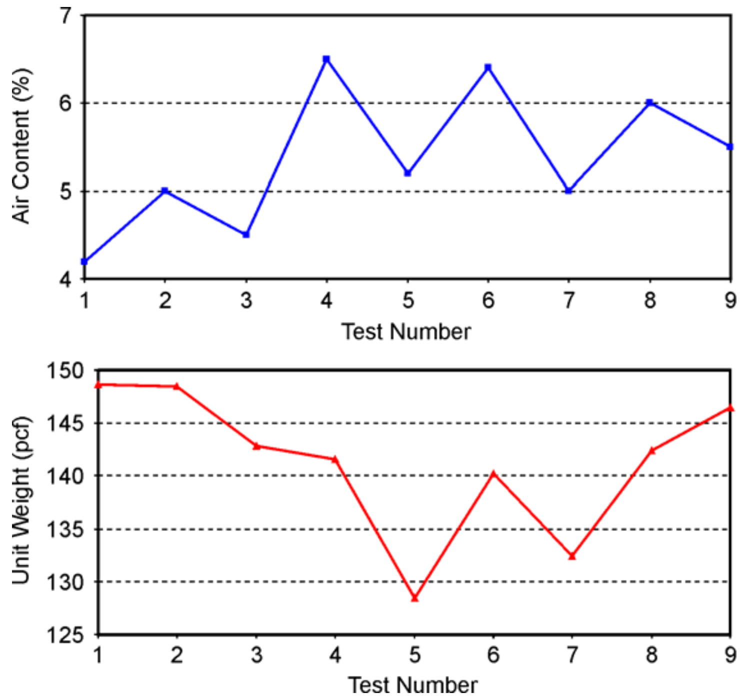

Figure 3. Anomalies in Relationship Between Air Content and Density (unit weight)

Industry Concerns

The main concerns of the industry were with the pay adjustment phase. The prevailing opinion is that the bonus is applied to the contractor and the penalty to the producer. VDOT can not affect this situation since this issue is between the contractor and the subcontractor. In addition, the verification of the failing test results of the hardened concrete by in situ testing is expected by the industry. It is thought that failing test results are mainly attributable to poor sampling and testing. With the ERS, each test result is accepted as valid unless a physical reason is noted.

Another concern is the definition of *lot* and *sublot*, which includes a day's production. It is questioned whether small amounts of concrete could affect the results and impart varying sublot sizes. It is also thought that testing small amounts is not economical. The ERS uses sublots of similar size, and a day's production that is small can be included in the subsequent or previous day's production. This concern is still being discussed in meetings with the industry.

Another issue is the class of concrete, which does not provide enough sublots when concrete is classified into A3 and A4. VDOT has been considering having one type of concrete for bridge structures irrespective of the ERS since substructures are also prone to distress and require the quality of the concrete to be as high as that for bridge decks. In addition, historical data show that the difference in strength between A3 and A4 concretes is much less than the 1,000 psi anticipated because of the high amount of cementitious material in the mixtures.

Similarly, the pilot projects in Phase II indicated a difference of 529 psi. If a single class of concrete is approved for bridge structures, more samples will be possible, increasing the probability of estimating the averages and reducing the confidence intervals in test results. New projects are planned where one type of concrete with strength and permeability requirements between those for A3 and A4 concretes will be specified for bridge decks and substructures.

In the ERS there is a provision that prevents a bonus if any lot has less than 90% PWL. The industry objects to this requirement, calling it the "death clause." However, this requirement was included to ensure that when a bonus is paid, the concrete will be long lasting without the need for any major maintenance of any of its sections during the service life of the structure. Any work in any location could result in the interruption of traffic for the entire structure.

CONCLUSIONS

- *Completed and ongoing pilot projects indicate the benefits of ERS.* Innovations are possible. Reduced cementitious material is consistent with the goals of green concrete.
- *Including the standard deviation in PF calculations is expected to reduce the variability of the product.*
- *To achieve quality concretes, emphasis should be on performance parameters rather than prescribed ingredients.*
- T*he contractor/producer has a better idea of the equipment and material at hand and should be responsible for designing and delivering the mixtures.*
- *Mixtures should be prequalified in advance of the placement, and QC before and during construction should be emphasized.*
- *The contractor should be responsible not only for the mixtures but also for the successful completion of the elements. In addition to the ERS, which is used to ensure proper mixtures, proper construction practices (handling and placement) and proper inspection are needed.*

RECOMMENDATIONS

1. *VDOT's Structure and Bridge Division and Materials Division should adopt the first two parts of the ERS (process control measures and VDOT approval of the mixture design) for use with bridge structures.*
2. *VDOT's Structure and Bridge Division and Materials Division should defer adopting the third part of the ERS (acceptance, including pay adjustments) until more projects including*

those with one class of concrete for bridge structures are conducted and the results of all pilot projects are discussed with the industry.

3. *VDOT's Materials Division should develop pilot projects using the ERS for concrete pavements, as was done for concrete used in bridges, before formally adopting the ERS as a VDOT specification for pavements.*

BENEFITS AND IMPLEMENTATION PROSPECTS

In ERSs, performance parameters are specified and the development of mixtures is left to the contractor/producer. ERSs give the authority and responsibility for producing a satisfactory concrete to the contractor/producer. Innovations and higher quality concrete are expected.

In addition, in cases of dispute, ERSs are more defensible than the prescriptive/method specifications. In prescriptive specifications, contractors argue that the agency has to accept the product since the approved mixture proportions were used and the inspector was present.

The prequalification of mixtures as specified in ERSs has been successfully implemented in VDOT pilot projects even though the pay factors were not enforced. The first two parts of the ERS (process control measures and VDOT approval of the mixture design) are permitted in VDOT projects upon request and are planned for inclusion in VDOT's current specifications as options.

ACKNOWLEDGMENTS

This study was conducted with funds administered by the Federal Highway Administration. Special thanks go to the contractors, concrete suppliers, FHWA, and VDOT personnel who spent many hours in the development of the provisions of the ERS. Chuck Hughes, formerly of VCTIR, laid the foundations of the statistical principles for the ERS; special thanks go to him for his valuable input that enabled the development of the ERS. The generous and extensive assistance of Larry Lundy and Hari Nair in the development of the ERS and the collection and evaluation of data are greatly appreciated. Special thanks go to Jim Gillespie of VCTIR for interpreting the statistical data and to Jackie Rosser formerly of VCTIR for evaluating the data.

REFERENCES

American Concrete Institute. ACI 318: Building Code Requirements for Structural Concrete and Commentary. Farmington Hills, MI, 2008.

ASTM International. ASTM C1064: Temperature of Freshly Mixed Hydraulic-Cement Concrete. Philadelphia, 2008.

ASTM International. ASTM C231: Air Content of Freshly Mixed Concrete by the Pressure Method. Philadelphia, 2009a.

ASTM International. ASTM C138: Density (Unit Weight), Yield, and Air Content (Gravimetric) of Concrete. Philadelphia, 2009b.

ASTM International. ASTM C31: Making and Curing Concrete Test Specimens in the Field. Philadelphia, 2009c.

ASTM International. ASTM C143: Slump of Hydraulic-Cement Concrete. Philadelphia, 2010.

ACI Committee on Responsibility in Concrete Construction. Guidelines for Authorities and Responsibilities in Concrete Design and Construction. *Concrete International,* Vol. 27, No. 4, April 2005, pp. 33-39.

Hughes, C.S., and Ozyildirim, C. *End-Result Specification for Hydraulic Cement Concrete.* VTRC 05-R29. Virginia Transportation Research Council, Charlottesville, 2005.

Kessler, R.J., Powers, R.G., Vivas, E., Paredes, M.A., and Virmani, Y.P. Surface Resistivity as an Indicator of Concrete Chloride Penetration Resistance. Paper presented at the Concrete Bridge Conference, St. Louis, Missouri, May 4-7, 2008.

Ozyildirim, C. *High-Performance Continuously Reinforced Concrete Pavements in Richmond and Lynchburg.* VTRC 08-R4. Virginia Transportation Research Council, Charlottesville, 2007.

Ozyildirim, C. Development of End Result Specifications for Concrete in Virginia. *Transportation Research Record: Journal of the Transportation Research Board*, No. 2164. Transportation Research Board of the National Academies, Washington, DC, 2010, pp. 76-81.

Ozyildirim, C. Virginia's End-Result Specifications. *Concrete International,* Vol. 33, No. 3, March 2011, pp. 41-45.

Transportation Research Board. *Glossary of Highway Quality Assurance Terms*. Transportation Research Circular Number E-C137. Transportation Research Board of the National Academies, Washington, DC, 2009.

Virginia Department of Transportation. *Road and Bridge Specifications*. Richmond, 1997.

Virginia Department of Transportation. Virginia Department of Transportation Special Provision for Hydraulic Cement Concrete Operations for Massive Construction. Richmond, September 14, 2004.

Virginia Department of Transportation. *Road and Bridge Specifications*. Richmond, 2007.

Virginia Department of Transportation, Materials Division. *Manual of Instructions*. Richmond, 2009.

APPENDIX A

VIRGINIA DEPARTMENT OF TRANSPORTATION
SPECIAL PROVISION FOR
HYDRAULIC CEMENT CONCRETE - END RESULT SPECIFICATION

December 3, 2007

Note: The price adjustments outlined in this Special Provision do not apply. In this pilot project, information will be gathered for fine tuning tolerances and pay factors for this end result specification. Acceptance/Rejection and handling of out-of-Specification material shall be addressed under the current Department policies and procedures.

SECTION 217- HYDRAULIC CEMENT CONCRETE of the Specifications is amended as follows:

Section 217.04 - Measurement of Materials is replaced with the following:

Section 217.04 - Quality Control - The Contractor shall provide process Quality Control adequate to produce work of acceptable quality. The Contractor shall perform process Quality Control sampling, testing, and inspection during all phases of the work at a rate sufficient to ensure that the end result work consistently conforms to the contract requirements and the minimum guidelines specified for that item of work.

For the Department's review and approval, the Contractor shall provide a process Quality Control Plan, hereinafter referred to as the "Plan." The Plan shall include a list and function of all personnel, equipment, supplies, and facilities necessary to obtain Quality Control samples, perform tests, and otherwise control the quality of the product to meet specified requirements contained herein. Any updates to the plan shall be subject to review and approval by the Department.

Quality Control testing shall be performed by the Contractor using certified technicians, as defined in Section 217.07, and where necessary in laboratories approved by the Department's Materials Division. Laboratory facilities and field equipment shall be maintained in accordance with Section 106.

The Plan shall describe the random sampling procedure that shall be used for obtaining Quality Control samples. The Contractor shall maintain a complete record of all Quality Control tests and inspections. All Quality Control samples shall be obtained in accordance with Department or ASTM procedures using a random sampling procedure except for check samples that shall be obtained if the Quality Control sample result indicates that the process is Out-of-Control. In the event a check sample is obtained, both the results from the original test and those from the check sample shall be individually noted as such and retained in the Contractor's database.

Control Charts of air content, slump, unit weight, and temperature shall be one part of the Plan and it shall be kept current, i.e., data shall be plotted within one working day of testing and displayed in a location designated by the Contractor. The location shall be accessible to the Engineer at all times. As a minimum, the Control Chart shall identify the test number, test date, control limits and the Contractor's test results. The Control Chart shall contain the plot of individual results and the moving average of the last 3 test results.

The Plan shall address all elements that affect the quality of the concrete including but not limited to the following: The Plan and its relevant items and the certified personnel will also be required during construction or the duration of the project.

a) Mix designs

b) Aggregate source

c) Quality of all components including aggregates, water, admixtures, and cementitious materials

d) Stockpile management

e) Mix properties, including temperature, air content, consistency, unit weight, and water/cementitious material ratio

f) Process Quality Control testing, including type of test and frequency

g) Compressive strength

h) Permeability

i) Computer batch ticket

Section 217.06 - Classification of Concrete Mixtures is amended as follows:

Table II-17 is replaced with the following:

TABLE II-17 Requirements for Hydraulic Cement Concrete

Class of Concrete		Design Min. Laboratory Compressive Strength at 28 Days (f'_c) (psi)	Design Max. Laboratory Permeability at 28 Days (coulombs)	Design Max. Laboratory Permeability at 28 Days (Over tidal water) (coulombs)	Air Content (%)
A5	Pre-stressed and other Special Designs[1]	5,000 to 10,000	1,500	1,500	4.5 ± 1.5
A4	General	4,000	2,500	2,000	6.5 ± 1.5
A4	Posts & rails[2]	4,000	2,500	2,000	7 ± 2
A3	General	3,000	3,500	2,000	6 ± 2
A3	Paving	3,000	3,500	3,500	6 ± 2
B2	Massive or Lightly Reinforced	2,200	NA	NA	4 ± 2
C1	Massive Un-reinforced	1,500	NA	NA	4 ± 2
T3	Tremie seal	3,000	NA	NA	4 ± 2

[1]When Class A5 concrete is used as the finished bridge deck riding surface, or when it is to be covered with asphalt concrete with or without waterproofing, the air content shall be 5.5 ± 1.5%.

[2]When necessary for ease in placement, aggregate No. 7 shall be used in concrete posts, rails, and other thin sections above the top of bridge deck slabs.

Note: The Contractor may substitute a higher class of concrete for that specified at the Contractor's expense.

When a High Range Water Reducing Admixture (HRWRA) is used, the upper limit air content shall be increased 1 percent.

Section 217.07 - Proportioning Concrete Mixtures is amended as follows:

Section 217.07 paragraphs 8, 14, and 15 are deleted.

Section 217.07 - Mix Design Approval is added

The Contractor shall submit Mix Designs for the various classes of concrete required to the Engineer for review, along with documentation indicating that the proposed mix designs shall meet the verification requirements listed in Table II-17. The documentation may be from past experience with the same materials and mix design or from trial as determined by the Engineer.

Mix design documentation shall consist, as a minimum, of the following:

a) Description and amount of cementitious materials.

b) Description of individual coarse aggregate sizes, aggregate source, bulk specific gravity, absorption, and gradation. A combined coarse aggregate blended gradation is permitted if approved by the Engineer.

c) Target water content by weight

d) Type and quantity of all admixtures.

e) Description of fine aggregate, aggregate source, bulk specific gravity, absorption gradation, and fineness modulus (FM).

f) Maximum water/cementitious material ratio

g) Target air content, consistency, and concrete temperature

h) Target concrete unit weight.

i) Target compressive strength

j) Target permeability

If the same mix design with the same material sources as those proposed for use have been used on other work within the previous 12 month period, certified copies of concrete test results from this work that indicate full compliance with these Special Provisions may be used instead of trial batches with the Engineer's permission. The guidelines in ACI 318 shall be followed. For example, the average results of 30 or more compressive strength tests shall be at least 1.34 standard deviations above the specified minimum compressive strength (f'_c). When less than 30 but 15 or more tests are available modification factor shall be applied. For 15 samples the modification factor is 1.16 indicating that the tests shall be 1.34 times 1.16 above the f'_c. For less than 15 samples the average shall be f'_c increased by 1200 psi. for concretes with compressive strengths between 3,000 and 5,000 psi. Similarly, the average results of 30 or more permeability test results shall be at least 1.34 standard deviations below the specified maximum permeability.

Mix design documentation using at least 3 cubic yard trial batches shall be based on the same materials and proportions proposed for use on the project. At least three trial batches of concrete with varying cementitious material and w/cm shall be prepared. Trial batch results shall be prepared at least 30 days prior to the start of concrete placement. For Mix Design approval based on a trial batch, ACI 318 shall be followed. For example, the average compressive strength of a minimum of three cylinders (one strength sample) taken from the trial batch for concrete with f'_c between 3,000 and 5,000 psi shall be at least 1200 psi (8.3 MPa) greater than the design minimum compressive strength requirement (f'_c) shown in Table II-17. The average permeability of a minimum of two permeability results (one permeability sample) shall be at least 500 coulombs less than the Upper Specification Limit (USL) for the design maximum permeability in Table II-17.

At the Contractor's option, the trial Mix Design may include compressive strength and permeability vs. time curves to indicate the relationship between these two parameters and time.

At the Engineer's option, verification may be done on an annual basis rather than on a project-by-project basis provided the sources, properties, ingredients, and proportions of the materials do not change.

Section 217.08 - Acceptance is replaced by the following:

Acceptance tests shall consist of: (1) the screening tests and (2) the pay factor tests. The contractor shall obtain those samples used for screening tests except when the same sample is being used for the pay factor tests. The Contractor shall conduct the screening tests. From each sublot, the Engineer shall take a split sample which will be used for pay factor tests and for both the independent assurance and independent verification tests on air content, slump, unit weight, and temperature.

Acceptance of structural, paving, and miscellaneous concrete shall be on a lot-by-lot basis as defined below:

(a) Definition of a Lot: For the purposes of this Special Provision a lot is defined as a limited quantity of concrete manufactured for a specific application such as bridge deck, substructure, or paving that is considered to be uniform and where the source of all major ingredients are the same, and the proportions of aggregates and cementitious materials are within 5% of the target design values and maintaining a 1 yd^3 volume. Variations within these limits do not require new mix design and trial batching.

1. Structural Concrete - A lot shall consist of a class of concrete and limited to 500 yd^3. A lot shall consist of sublots. Each sublot shall consist of a maximum of 100 yd^3 of a particular class of concrete, and there shall be at least one sublot for each day's placement. One compressive strength sample and one permeability sample shall be obtained from each sublot on a randomly selective basis. Alternatively, for small projects, i.e., up to 100 yds^3 total, two samples shall be selected on a random basis and the definition of sublot shall not apply. A strength sample is defined as the average of 3 cylinders and a permeability sample as the average of 2 cylinders.

2. Paving Concrete - A lot shall consist of one lane-mile of pavement. Each lot shall consist of sublots defined as 0.2 mile of pavement. One set of compressive strength and permeability samples shall be taken from each sublot.

3. Miscellaneous concrete – A lot shall consist of a class of concrete placed within two weeks. A sublot shall consist of 250 yds^3 of a class of concrete.

(b) Acceptance Sampling and Testing

Acceptance tests shall consist of (1) the screening tests and (2) the pay factor tests. Screening tests shall be for air content, unit weight, slump, and temperature and shall be sampled from each truckload by the Contractor. VDOT will conduct comparative testing. Information on comparative testing is available in the "End Result Sampling and Testing Plan", which is available upon request from VDOT. Screening tests shall be used to determine whether or not the truck can discharge its contents on the project. Tests made to determine the pay factor shall be made on a sublot basis by the Department for different construction activities. Pay factor tests on strength and permeability are evaluated using percent within limits (PWL). Pay factors of ride quality (applies only if Rideability Special Provision is included) and thickness (refers to thickness specification for pavements) uses existing VDOT specifications. Screening and acceptance tests are described as follows:

1. Screening Tests

   Sampling and testing for Air Content, Unit weight, Slump and Temperature: Each load of structural concrete during each production day shall be sampled and tested by the Contractor for air content, unit weight, slump, and temperature. Paving concrete shall be sampled for the first three loads per day and then randomly once for each 100 yd^3 of concrete. Miscellaneous concrete shall be sampled for each load. The Contractor is responsible for furnishing concrete within the air content, unit weight, slump, and temperature ranges established for the project. All batches with either air content, slump, or temperature not in compliance with Section 217 shall be rejected and removed from the job. The sample secured for the fresh and hardened concrete tests shall be taken after at least 2 ft^3 of concrete has been discharged from the delivery vehicle.

   a. Air Content Tests: Air content tests shall be performed by the Contractor to ensure that specification requirements are consistently being complied with for each class of concrete.

      Air content shall be determined after all the mix water has been added in accordance with the requirements of ASTM C231 or C173.

      If the determination of any test yields a result that is outside the allowable range for air content, the following procedure will be used:

      1. The Contractor has the option of (1) immediately performing a recheck determination or (2) adding air-entraining admixture to bring the air content within specification limits. Air-entraining admixture may be added one time to the concrete in those loads that are on site or in transit. For option (1), if the average of the two air content results is within the specification limits for air content the material can be used; if the average of the two tests is outside this limit the material shall be rejected. For option (2), the concrete with the additional material shall be sampled as a new truckload and the above acceptance procedure used. If the test result is outside the allowable range for air content, the material shall be rejected.

      2. If the load is rejected, the Contractor's representative shall notify the producer of the test results through a pre-established means of communication.

   b. Unit Weight: Unit weight shall be determined in accordance with ASTM C 138. The unit weight obtained shall be higher than 95% of the value calculated from the mixture proportions.

   c. Slump: Slump shall be determined in accordance with ASTM C 143. The slump values shall be +/- 2 inches of the target value established by the Contractor for the specific mix design.

   d. Temperature: Temperature of the freshly mixed concrete shall be determined in accordance with ASTM C 1064. The temperature values shall meet the requirements set for the project.

2. Pay Factor Tests

   a. Compressive Strength Tests: The 28-day strengths specified in Table II-17 shall be the strengths used in the design calculations. The Engineer will verify design strengths by tests made in accordance with the requirements of ASTM C31, C39, or C42.

      The Contractor shall provide a storage chamber at his expense for temporary storage of the concrete cylinders. The chamber shall be designed to maintain test cylinders in a continuously moist condition within a temperature range specified in the ASTM requirements and shall be equipped with a continuously recording thermometer. The chamber shall be located near the concrete placement site in an area where test cylinders will not be subject to vibration and shall be of sufficient size or number to store, without crowding or wedging, the required number of test cylinders as determined by the Contractor based on his plan of operations and approved by the Engineer.

      When use of high-early-strength hydraulic cement concrete is authorized, it shall conform to the requirements of Table II-17. except that the 28-day strength shall be obtained in 7 days. Types I, II, or III cements may be used to produce high-early-strength concrete, however, the total cementitious material content shall not exceed 850 lbs/yd^3.

   b. Permeability Tests: The 28-day permeability values specified in Table II-17 shall be the target values required for durability as determined by VTM 112.

3. Acceptance Criteria

   Acceptance for compressive strength and permeability shall be based on the Quality Index (Q) calculated using the results of the tests per lot described above. The Q uses both the average and the standard deviation within each lot to estimate the population parameters and determine the percentage of the lot within specification limits. The Acceptable Quality Level (AQL) is that quality of concrete for which the Contractor will receive 100 percent pay. Rejectable Quality Level (RQL) is that quality of concrete requiring removal and replacement by the Contractor or for which the Contractor will provide remedial action. The AQL has been established at 90 Percent Within Limits (PWL) and the RQL at 50 PWL. The Q shall be calculated using the following equations:

   $Q_L = (\overline{X} - LSL)/s$ $\qquad$ $Q_U = (USL - \overline{X})/s$

   Where:
   Q_L is the Lower Quality Index*
   Q_U is the Upper Quality Index*
   $\overline{X}$ is the average
   s is the standard deviation
   LSL is the Lower Specification Limit shown below
   USL is the Upper Specification Limit shown below
   Q_L shall be used for strength and Q_U shall be used for permeability.

Upper and Lower Specification Limits

Class of Concrete	LSL for Strength, psi	USL for Permeability, coulombs	USL for Permeability over tidal water, coulombs
A5	5500	1200	1200
A4	4500	2200	1700
A3	3800	3200	1700

Note: For higher design compressive strengths add 500 psi (e.g., for 8,000 psi concrete, LSL is 8,500 psi)

Q_L and Q_U are used to enter Table II-18 (n=3, 4, and 5 are given, n=6 or higher will be provided) for the estimation of the lot PWL. The PWL is, in turn, used to determine the pay factor through the appropriate pay factor equation as discussed below.

All material that has a PWL less than 50 shall be accepted at the calculated pay factor or rejected and removed from the project at the Engineer's option. If the rejectable product can be corrected, it may be accepted upon correction, at the Engineer's option.

a. Acceptable compressive strength

1. When the number of samples tested (n) on the lot is 3 or more, the Q_L and Q_U shall be used to estimate the PWL and pay factor.

2. When the number of samples tested on the lot is less than 3, the acceptable average compressive strength for a sample size of n=2 shall be the LSL + 200 psi; and for a sample size of n=1 the minimum acceptable compressive strength shall be the LSL.

TABLE II-18 PERCENT WITHIN LIMITS ESTIMATION TABLE
Variability Unknown Procedure, Standard Deviation Method
for n=3

Q	0.00	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09
0.0	50.00	50.28	50.55	50.83	51.10	51.38	51.65	51.93	52.21	52.48
0.1	52.76	53.04	53.31	53.59	53.87	54.15	54.42	54.70	54.98	55.26
0.2	55.54	55.82	56.10	56.38	56.66	56.95	57.23	57.51	57.80	58.08
0.3	58.37	58.65	58.94	59.23	59.51	59.80	60.09	60.38	60.67	60.97
0.4	61.26	61.55	61.85	62.15	62.44	62.74	63.04	63.34	63.65	63.95
0.5	64.25	64.56	64.87	65.18	65.49	65.80	66.12	66.43	66.75	67.07
0.6	67.39	67.72	68.04	68.37	68.70	69.03	69.37	69.70	70.04	70.39
0.7	70.73	71.08	71.43	71.78	72.14	72.50	72.87	73.24	73.61	73.98
0;8	74.36	74.75	75.14	75.53	75.93	76.33	76.74	77.16	77.58	78.01
0.9	78.45	78.89	79.34	79.81	80.27	80.75	81.25	81.75	82.26	82.79
1.0	83.33	83.89	84.47	85.07	85.69	86.34	87.02	87.73	88.49	89.29
1.1	90.16	91.11	92.18	93.40	94.92	97.13	100.00	100.00	100.00	100.00

VALUES IN BODY OF TABLE ARE ESTIMATES OF PERCENT WITHIN LIMITS CORRESPONDING TO SPECIFIC VALUES OF Q = (AVERAGE – LOWER LIMIT) / (STANDARD DEVIATION OR Q = (UPPER LIMIT – AVERAGE) / (STANDARD DEVIATION). FOR NEGATIVE Q VALUES, THE TABLE VALUES MUST BE SUBSTRACTED FROM 100.

TABLE II-18 PERCENT WITHIN LIMITS ESTIMATION TABLE
Variability Unknown Procedure, Standard Deviation Method
for n=4

Q	0.00	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09
0.0	50.00	50.33	50.67	51.00	51.33	51..67	52.00	52.33	52.67	53.00
0.1	53.33	53.67	54.00	54.33	54.67	55.00	55.33	55.67	56.00	56.33
0.2	56.67	57.00	57.33	57.67	58.00	58.33	58.67	59.00	59.33	59.67
0.3	60.00	60.33	60.67	61.00	61.33	61.67	62.00	62.33	62.67	63.00
0.4	63.33	63.67	64.00	64.33	64.67	65.00	65.33	65.67	66.00	66.33
0.5	66.67	67.00	67.33	67.67	68.00	68.33	68.67	69.00	69.33	69.67
0.6	70.00	70.33	70.67	71.00	71.33	71.67	72.00	72.33	72.67	73.00
0.7	73.33	73.67	74.00	74.33	74.67	75.00	75.33	75.67	76.00	76.33
0.8	76.67	77.00	77.33	77.67	78.00	78.33	78.67	79.00	79.33	79.67
0.9	80.00	80.33	80.67	81.00	81.33	81.67	82.00	82.33	82.67	83.00
1.0	83.33	83.67	84.00	84.33	84.67	85.00	85.33	85.67	86.00	86.33
1.1	86.67	87.00	87.33	87.67	88.00	88.33	88.67	89.00	89.33	89.67
1.2	90.00	90.33	90.67	91.00	91.33	91.67	92.00	92.33	92.67	93.00
1.3	93.33	93.67	94.00	94.33	94.67	95.00	95.33	95.67	96.00	96.33
1.4	96.67	97.00	97.33	97.67	98.00	98.33	98.67	99.00	99.33	99.67
1.5	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

VALUES IN BODY OF TABLE ARE ESTIMATES OF PERCENT WITHIN LIMITS
CORRESPONDING TO SPECIFIC VALUES OF Q = (AVERAGE – LOWER LIMIT) /
(STANDARD DEVIATION OR Q = (UPPER LIMIT – AVERAGE) / (STANDARD DEVIATION).
FOR NEGATIVE Q VALUES, THE TABLE VALUES MUST BE SUBSTRACTED FROM 100.

TABLE II-18 PERCENT WITHIN LIMITS ESTIMATION TABLE
Variability Unknown Procedure, Standard Deviation Method
for n=5
(Tables for n=6 or higher will be provided upon request).

Q	0.00	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09
0.0	50.00	50.36	50.71	51.07	51.42	51.78	52.13	52.49	52.85	53.20
0.1	53.56	53.91	54.27	54.62	54.98	55.33	55.69	56.04	56.39	56.75
0.2	57.10	57.46	57.81	58.16	58.52	58.87	59.22	59.57	59.92	60.28
0.3	60.63	60.98	61.33	61.68	62.03	62.38	62.72	63.07	63.42	63.77
0.4	64.12	64.46	64.81	65.15	65.50	65.84	66.19	66.53	66.87	67.22
0.5	67.56	67.90	68.24	68.58	68.92	69.26	69.60	69.94	70.27	70.61
0.6	70.95	71.28	71.61	71.95	72.28	72.61	72.94	73.27	73.60	73.93
0.7	74.26	74.59	74.91	75.24	75.56	75.89	76.21	76.53	76.85	77.17
0.8	77.49	77.81	78.13	78.44	78.76	79.07	79.38	79.69	80.00	80.31
0.9	80.62	80.93	81.23	81.54	81.84	82.14	82.45	82.74	83.04	83.34
1.0	83.64	83.93	84.22	84.52	84.81	85.09	85.38	85.67	85.95	86.24
1.1	86.52	86.80	87.07	87.35	87.63	87.90	88.17	88.44	88.71	88.98
1.2	89.24	89.50	89.77	90.03	90.28	90.54	90.79	91.04	91.29	91.54
1.3	91.79	92.03	92.27	92.51	92.75	92.98	93.21	93.44	93.67	93.90
1.4	94.12	94.34	94.56	94.77	94.98	95.19	95.40	95.61	95.81	96.01
1.5	96.20	96.39	96.58	96.77	96.95	97.13	97.31	97.48	97.65	97.81
1.6	97.97	98.13	98.28	98.43	98.58	98.72	98.85	98.98	99.11	99.23
1.7	99.34	99.45	99.55	99.64	99.73	99.81I	99.88	99.94	99.98	100.00

VALUES IN BODY OF TABLE ARE ESTIMATES OF PERCENT WITHIN LIMITS
CORRESPONDING TO SPECIFIC VALUES OF Q = (AVERAGE – LOWER LIMIT) /
(STANDARD DEVIATION OR Q = (UPPER LIMIT – AVERAGE) / (STANDARD DEVIATION).
FOR NEGATIVE Q VALUES, THE TABLE VALUES MUST BE SUBSTRACTED FROM 100.

b. Acceptable permeability

   1. When the number of samples tested (n) on the lot is 3 or more, the Q_L and Q_U shall be used to estimate the PWL and pay factor.

   2. When the number of samples tested on the lot is less than 3, the acceptable average permeability for a sample size of n=2 shall be the USL - 100 coulombs, and for a sample size of n=1, USL for permeability shall be met.

c. Acceptable Ride Quality - Refer to the Rideability Special Provision if provided in the contract documents to determine price adjustment.

d. Acceptable thickness – Refer to the thickness specifications for pavements (Section 316.06) to determine price adjustment.

4. Basis of Payment

   a. When the PWL for the 28-day minimum design compressive strength and design maximum permeability of the lot is equal to or exceeds 50, the pay factor shall be determined by the following equation:

      Pay Factor for Individual Properties = 82 + 0.2 (PWL)

   b. The Lot Pay Factor shall be an average of the individual pay factors for compressive strength, permeability.

      The Average Pay Factor = Pay Factor for Individual Properties/N,
      Where N = number of individual properties.
      The Average Pay Factor = C_1(Permeability) +C_2(Strength) divided by C_1+C_2
      C_1=weighted factor for permeability = 1.0
      C_2=weighted factor for strength = 1.0

   c. To receive a pay factor greater than 100 percent, all individual properties shall be 90 PWL or more for all lots in the project.

   d. For compressive strength and/or permeability results of lots for samples of size n = 1 or 2, material meeting the requirements described under acceptable compressive strength and acceptable permeability shall be accepted at the full unit bid price.

   e. The total pay quantity is determined by multiplying the Average Pay Factor by the unit bid price and adding the price adjustment for pavement thickness and ride quality.

APPENDIX B

STRENGTH AND PERMEABILITY DATA FROM DISTRICTS FOR A3 AND A4 CONCRETES

A3 Compressive Strength (psi)

District[a]	Mean	Std. Dev.	Max.	Min.	n	LSL	Q Range	PWL Range	Avg. PWL	Avg. PF (%)
Richmond	4570	560	6000	3400	46	3800	0.59 to 5.85	70.61 to 100	91.14	100.20
Fredericksburg	3850	600	4950	2470	19	3800	-0.39 to 0.34	36.23 to 62.03	51.95	92.40
Fredericksburg	4700	530	6030	3720	18	3800	0.99 to 6.78	83.34 to 100	95.76	101.20
Lynchburg	4010	460	4573	3359	7	3800	0.46[b]	66.87[b]	66.87[b]	95.40
Culpeper	4870	570	5770	4200	9	3800	1.47 to 2.09	99 to 100	99.5	101.90
Bristol	4890	460	5870	4170	24	3800	2.18 to 3.04	100 to 100	100	102.00
Staunton	4940	630	6260	4040	15	3800	1.66 to 2.39	98.85 to 100	99.61	101.90
Hampton Roads	4760	550	6000	3550	82	3800	0.83 to 5.41	78.44 to 100	90.45	101.20
Northern Virginia	5230	800	8050	3500	54	3800	1.07 to 6.83	85.67 to 100	88.67	101.30
Average	4647	573	5945	3601						99.72
Weighted average	4759									100.42

n = number of sublots; LSL = lower specification limit; Q = quality index; PWL = percent within limits; PF = pay factor.
[a] Some districts had more than one project.
[b] One lot only.

A3 Permeability (coulombs)

District [a]	Mean	Std. Dev.	Max.	Min.	n	USL [b]	Q Range	PWL Range	Avg. PWL	Avg. PF (%)
Richmond	456	140	1027	249	46	1700	4.72 to 51.57	100 to 100	100	102.00
Fredericksburg	1953	670	3889	1076	19	3200	0.90 to 8.11	80.62 to 100	95.7	101.00
Fredericksburg	1236	335	1964	823	18	3200	3.72 to 25.01	100 to 100	100	102.00
Lynchburg	2670	1150	4613	764	7	3200	0.46 [c]	66.87 [c]	66.87 [c]	95.40
Culpeper	1388	475	2174	783	9	3200	3.62 to 6.76	100 to 100	100	102.00
Bristol	742	215	1354	451	24	3200	14.47 to 44.52	100 to 100	100	102.00
Staunton	2080	430	2714	1312	15	3200	2.00 to 4.41	100 to 100	100	102.00
Hampton Roads	460	173	880	115	82	1700	4.09 to 18.96	100 to 100	100	102.00
Northern Virginia	1075	345	1790	190	26	3200	4.88 to 39.55	100 to 100	100	102.00
Average	1340	437	2267	640						101.05
Wt. avg. all	919									101.73
Wt. avg. USL 1700	459									102.00
Wt. avg. USL 3200	1419									101.45

n = number of sublots; USL = upper specification limit; Q = quality index; PWL = percent within limits; PF = pay factor.

[a] Some districts had more than one project.

[b] Tidal water has a USL of 1700 coulombs.

[c] One lot only.

A4 Compressive Strength (psi)

District [a]	Mean	Std. Dev.	Max.	Min.	n	LSL	Q Range	PWL Range	Avg. PWL	Avg. PF (%)
Richmond	4820	680	6350	3270	161	4500	-1.03 to 5.02	12.22 to 100	64.62	94.90
Fredericksburg	6210	645	7040	5530	6	4500	2.65 [b]	99.98 [b]	99.98 [b]	102.00
Fredericksburg	6100	510	6840	5760	4	4500	3.14 [b]	100 [b]	100 [b]	102.00
Fredericksburg	5580	575	6710	4550	24	4500	1.67 to 2.94	98.98 to 100	99.58	101.90
Culpeper	5540	810	6610	4540	6	4500	1.21[b]	89.5[b]	89.5[b]	99.90
Bristol	5080	860	6760	3780	10	4500	0.43 to 1.80	65.15 to 100	98.50	82.57
Staunton	6790	1400	9340	4700	8	4500	1.39 to 3.15	96.33 to 100	98.15	101.60
Staunton	5030	535	5760	4250	16	4500	0.47 to10.64	34.33 to 100	69.55	97.40
Salem	5010	300	5620	4340	29	4500	1.14 to 4.32	87.63 to 100	96.52	101.30
Hampton Roads	5670	743	7610	4220	80	4500	0.75 to 4.78	75.89 to 100	95.13	101.00
Northern Virginia	5660	680	6700	4530	23	4500	0.95 to 3.86	82.14 to 100	95.31	100.60
Northern Virginia	6000	760	7660	4330	30	4500	1.45 to2.97	95.19 to 100	98.42	101.70
Average	5624	740	6974	4360						98.91
Weighted average	5288									98.04

n = number of sublots; LSL = lower specification limit; Q = quality index; PWL = percent within limits; PF = pay factor.

[a] Some districts had more than one project.

[b] One lot only.

A4 Permeability (coulombs)

District [a]	Mean	Std. Dev.	Max.	Min.	n	USL [b]	Q Range	PWL Range	Avg. PWL	Avg. PF (%)
Richmond	430	155	1098	177	160	1700 [c]	3.21 to 90.81	100 to 100	100	102.00
Fredericksburg	1090	160	1235	830	6	2200	6.99	100 [c]	100	102.00
Fredericksburg	1060	48	1130	1020	4	2200	23.51	100 [c]	100	102.00
Fredericksburg	870	180	1300	565	24	2200	6.18 to 19.47	100 to 100	100	102.00
Bristol	1080	300	1476	619	7	2200	2.69 to 12.27	100 to 100	100	102.00
Staunton	1695	190	2028	1435	8	2200	1.49 to 5.96	99.67 to 100	99.84	102.00
Staunton	3150	1020	5100	1480	16	2200	-1.48 to -0.23	0 to 42.33	13.9	84.80
Salem	390	72	575	241	29	2200	21.17 to 51.60	100 to 100	100	102.00
Hampton Roads	440	174	1363	241	57	1700 [c]	2.56 to 33.19	100 to 100	100	102.00
Northern Virginia	940	200	1340	540	19	2200	3.60 to 26.39	100 to 100	100	102.00
Northern Virginia	840	200	1050	630	6	2200	22.39 to 216	100 to 100	100	102.00
Average	1090	245	1609	707						100.44
Wt. avg. all	688									101.18
Wt. avg. USL 1700	433									102.00
Wt. avg. USL 2200	1155									99.69

n = number of sublots; USL = upper specification limit; Q = quality index; PWL = percent within limits; PF = pay factor.

[a] Some districts had more than one project.

[b] Tidal water has a USL of 1700 coulombs.

[c] One lot only.