Experimental Case Study Demonstrating Advantages of Performance Specifications

Prepared by:
Karthik Obla, PhD, PE
Colin Lobo, PhD, PE

Experimental Case Study Demonstrating Advantages of Performance Specifications

A Project that Supports the NRMCA Prescription-to-Performance (P2P) Initiative

Report to the RMC Research Foundation
Project 04-02
January 2006

Prepared by

Karthik Obla[1] and Colin Lobo [2]

[1] Director of Research and Materials Engineering, National Ready Mixed Concrete Association
[2] Vice President of Engineering, National Ready Mixed Concrete Association

TABLE OF CONTENTS

Executive Summary

NRMCA has an initiative to evolve specifications for concrete construction from prescriptive requirements to performance-based concepts for concrete mixtures. One of the goals of the P2P initiative has been to develop technical data that demonstrate the benefits of performance-based specifications that could be used to support changes in codes and specifications. A review group composed of members from the NRMCA's Research Engineering and Standards Committee reviewed the scope of this proposed study and approved the NRMCA Research Laboratory to undertake this research with funding provided by the RMC Research Foundation. This final report has been reviewed and approved by the review group.

Three scenarios where prescriptive specifications prevail were chosen – Concrete Floor Slab Construction; Concrete Bridge Deck Construction using high performance concrete (HPC); Prescriptive provisions for durability in ACI 318, *Building Code for Structural Concrete.* Concrete mixtures were prepared according to typical prescriptive requirements for each scenario and compared to mixtures that satisfy the intended performance attributes. Fresh and hardened concrete properties were measured and compared.

For the Floor Slab mixtures the prescriptive requirements chosen for the control condition were 28-day compressive strength based on strength over design factor of 1200 psi, a maximum water to cementitious ratio (w/cm), slump limits, continuous combined aggregate grading meeting 8-18 limits, and prohibition of the use of supplementary cementitious materials (SCMs). In contrast the performance requirements were 28 day compressive strength based on past test records, slump, shrinkage and initial setting time with no restrictions on materials or mixture proportions. Four alternative performance-based mixtures were evaluated and compared to the control prescriptive mixture. All the performance mixtures met the performance requirements. The use of prescriptive requirements such as maximum w/c and strength over design increased the cementitious contents of the prescriptive mixtures substantially resulting in potential problems due to the high paste content. This and the non use of SCMs made the prescriptive mixtures less competitive as compared to the performance mixtures. The prescriptive continuous aggregate grading requirement also did not show any significant performance benefit.

For the HPC bridge deck mixtures, based on a typical state highway agency specification, the prescriptive requirements for the control condition were 28 day compressive strength, a maximum w/cm, minimum total cementitious content, specified dosages for fly ash and silica fume, slump, air content, and a Rapid Chloride Permeability value. In contrast the performance requirements were 28 day compressive strength, slump, air content, shrinkage, and a Rapid Chloride Permeability value with no restrictions on materials or mixture proportions. Three alternative performance-based mixtures were evaluated and compared to the control prescriptive mixture. All the performance mixtures met the performance requirements. Performance mixtures had lower cementitious contents and silica fume dosages as compared to prescriptive mixtures. The reduced paste content of these mixtures ensured a lower drying shrinkage, lower HRWR dosage, lesser stickiness and a lower material cost. Performance mixtures also had similar or better rapid chloride permeability, rapid migration and chloride diffusion coefficient values, all important indicators to protect from corrosion of reinforcing steel.

For the ACI 318 Code the primary prescriptive provision was the w/cm as dictated by the provisions in the Building Code. The control condition used a Portland cement mixture. Three performance based alternatives were designed at lower cementitious materials content and with the used of supplementary cementitious materials. All mixtures had the same w/cm ratio. It was clearly shown that at the same w/cm considerable differences in concrete drying shrinkage, rapid chloride permeability, rapid migration and chloride diffusion coefficient can be attained. This portion of the study illustrates that factors beyond limiting the w/cm ratio can be employed to assure improved durability and optimized concrete mixtures for intended performance. The use of SCMs and chemical admixtures substantially affects concrete durability. This portion of the study will be used to support code change proposals that support performance alternatives to the current prescriptive provisions.

In summary the project developed substantial experimental data which helped to conclude that performance mixtures have equal or better performance as compared to prescriptive mixtures and can allow for significant optimization of mixture proportions by knowledgeable and qualified concrete producers. It also became clear that the use of minimum cementitious contents and the prescribed use of SCMs were the two main prescriptive requirements that significantly affected the producer’s freedom in designing optimum concrete mixtures to attain the required performance.

The results of this study will be presented at three different national conferences and published in four national and international journals and magazines. These references have been provided under the list of references included in this article.

Introduction

NRMCA has an initiative to evolve specifications from prescriptive requirements to performance-based concepts for concrete mixtures. The Prescription to Performance (P2P) Initiative has been identified by concrete producers as an important initiative that will elevate the quality of concrete construction by providing qualified concrete producers the ability to use their expertise to optimize concrete mixtures for intended performance of concrete structures. Typically this will also result in optimized cost for required performance. This higher level of control will also elevate the level of performance of the ready mixed concrete producer by establishing quality control processes and in product development and optimizing mixtures. The current system of prescriptive specifications does not offer any incentive for a ready mixed concrete quality management system or product development. It follows a "one-size-fits-all" approach and limits the ability to optimize concrete mixtures for performance. Frequently the specifications include conflicts and are not clearly defined. This results in call backs, change orders and generally reduces the level of credibility of concrete construction relative to other construction products such as steel and wood.

One of the goals of the P2P Initiative has been to develop technical data that demonstrate the benefits of performance based specifications that could be used to support changes in codes and specifications. This study conducted by the NRMCA Research Laboratory is one attempt to quantify comparative properties of concrete mixtures optimized for performance that may not comply with typical prescriptive provisions in specifications for concrete construction. The study was conducted to address three cases:

1. Concrete Floor Slab Construction
2. Concrete Bridge Deck Construction using high performance concrete (HPC), and
3. An evaluation of the current prescriptive provisions for durability in ACI 318, *Building Code for Structural Concrete.*

The study compares concrete mixtures according to the current typical prescriptive specifications or code requirements and demonstrates the benefits by developing concrete mixtures to intended performance criteria.

Concrete mixtures were prepared according to prescriptive requirements of an example specification for each application and compared to mixtures that satisfy the intended performance attributes. Fresh and hardened concrete properties were measured and compared. This comparison demonstrates the benefits and optimization of concrete mixtures for performance over prescriptive provisions. Funding for the study was provided by the RMC Research Foundation.

Experimental Study

This research study was conducted at the NRMCA Research Laboratory. The experimental program is divided into three cases.

Case 1 considers a typical floor slab specification from a major commercial owner. A concrete mixture was first designed to meet the prescriptive specification. Four alternative concrete mixtures were developed that considered various options to optimize the mixtures. These four mixtures did not meet the prescriptive criteria. The concrete performance most relevant to that application such as workability to include segregation potential and finishability, setting time, strength, and shrinkage to evaluate the potential for curling, are compared.

Case 2 considers a HPC bridge deck specification used by a major state department of transportation. A prescriptive mixture that complied with the typical specification requirements of the state was first designed. Three alternative optimized mixtures that did not meet the prescriptive specification were developed. The concrete performance most relevant to that application such as strength, shrinkage and durability are compared. Durability included attaining a required air content and various methods that measured the transport properties of the concrete that impact the potential corrosion of steel reinforcement.

Case 3 evaluates some of the prescriptive provisions of the ACI 318 Building Code. Provisions for durability in the code primarily restrict the w/cm and compressive strength of concrete mixtures as a means to control its permeability. Four mixtures were designed to evaluate if that approach is valid given the advances that have been made in recent decades with the widespread use of chemical admixtures and supplementary cementitious materials.

In this report the term paste content represents the volume percent of cementitious materials and the water in the mixture. Air content is not included in the volume of paste.

Materials

The following materials were used in the study:

- ASTM Type I portland cement, Lot #7970
- ASTM C 618 Class F fly ash, Lot #7948
- ASTM C 989 ground granulated blast furnace slag, Lot #7945
- ASTM C 1240 silica fume, Lot#7977
- An ultra fine fly ash conforming to ASTM C 618, Class F, Lot#7976
- ASTM C 260 tall oil air entraining admixture, Lot#7941
- ASTM C 494 Type A lignin-based water reducing admixture, Lot#7974
- ASTM C 494 Type F naphthalene sulfonate high range water reducing admixture, Lot#7975
- ASTM C 33 natural sand, Lot # 7958
- ASTM C 33 No. 67 crushed stone dolomitic limestone coarse aggregate, Lot#7973
- Additionally, for the floor slab mixtures the following aggregates were used:
- ASTM C 33 No. 467 crushed stone dolomitic limestone coarse aggregate, Lot#7963
- ASTM C 33 No. 8 crushed stone dolomitic limestone coarse aggregate, Lot#7966
- Aggregate sizes ¾ in to ½ in

The aggregate characteristics are provided in Table 1.

Mixing Concrete

A 3.5 cu. ft. revolving drum mixer was used to mix the concrete. Concrete batch size was kept at 2.9 cu. ft. Concrete was mixed in accordance with ASTM C 192.

When fly ash, slag, and silica fume were used in the concrete mixtures they were added to the mixer immediately after the cement. For the HPC bridge deck mixtures (Case 2) and ACI 318 mixtures (Case 3) Type A water reducing admixture was mixed with the water and batched with the coarse aggregate prior to adding the sand and cementitious materials. Air entraining admixture was added on top of the sand.

The HPC bridge deck mixtures (Case 2) and ACI 318 mixtures (Case 3) were mixed to a target w/cm ratio. The floor slab mixtures (Case 1) were mixed to a target slump with a varying quantity of mixing water.

Type F high range water reducer (when used) was added only after the concrete had mixed for about 2 minutes and a slump of about ½-inch had been ascertained visually. When HRWR admixtures were used concrete was mixed for an additional 2 minutes over the 3-3-2 mixing cycle per ASTM C 192. HRWR dosage was adjusted to achieve the desired slump. For the two ACI 318 mixtures that did not contain the HRWR no mix adjustments were made and the slump as achieved was measured.

Testing

Table 2 gives a quick overview of the various tests conducted as part of this research study. ASTM or AASHTO standardized testing procedures were followed to the extent possible. Non-standardized tests and deviations from ASTM standards (if any) are described as applicable. The NRMCA research laboratory participates in proficiency sample testing of the Cement and Concrete Reference Laboratory (CCRL), is inspected biannually for conformance to the requirements of ASTM C 1077 and maintains its accreditation under the AASHTO Laboratory Accreditation Program.

Fresh concrete tests

All concrete batches were tested for slump, ASTM C 143, air content, C 231, density, C 138 and temperature, C 1064.

Initial setting time was measured for the floor slab mixtures (Case 1), in accordance with ASTM C 403. The sieved mortar for the initial setting time test (ASTM C 403) was transferred to a 70ºF, 50% relative humidity room where they were stored until they achieved final set.

For the floor slab mixtures, a method to evaluate the relative finishability was used. The result of the method was a finishability index, based on the operator's observation. The finishability index determination involved casting 2x1 foot concrete slabs at 4 inches thickness and finishing by hand with a wooden finishing tool. A "finishability rating" value between 1 to 5 was assigned as a measure of the concrete finishability with the following criteria (5=Excellent to 1=Poor). A finished slab is shown in Figure 1.

For the floor slab mixtures, a test was devised to evaluate the propensity of the mixture for segregation. In the segregation test, a concrete 6x12 cylinder was cast after the concrete slump was raised to between 5 and 6 inches. The cylinder was vibrated using an internal vibrator. The cylinder was sawed in two after 7 days of moist curing and the density of the top and bottom halves were determined by weighing them in air and submerged in water. Difference in density was presumed to be a result of segregation, i.e. migration of the coarse aggregate particles towards the bottom. Since the calculated density of coarse aggregate particles (specific gravity x unit wt. of water) in this case is much denser (177 lbs/ft^3) as compared to the mortar (calculated to be about 131 lb/ft^3), this was used to estimate the variation in coarse aggregate content between the top and bottom specimens from the difference in density. The results reported are the average of 2 test specimens.

Hardened concrete Tests

Compressive strength tests for concrete mixtures were conducted in accordance with ASTM C 39. Specimen size used was 4 x 8 inch cylindrical specimens. Test specimens were transferred to the 100% humidity room as soon as they were made and cured until the test age. Neoprene caps of 70 durometer hardness were used to cap the test specimens in accordance with ASTM C 1231. Strength test results reported are the average of 2 test cylinders tested at the same age.

Length change of concrete due to drying shrinkage was tested by ASTM C 157. Prismatic specimens 3 x 3 x 11 inches with embedded studs were used to measure the length change, using a gage length of 10 inches between the insides of the studs. The shrinkage test specimens were moist cured for 7 days and after that they were stored in at 70 ºF and a relative humidity of 50%. Length change measurements were obtained at various periods of air drying as indicated in the reported results. The length change reported is the average of 2 specimens except for the floor slab mixtures in which 3 specimens were tested.

Durability Tests

The following tests were conducted to measure various indicators of transport properties of concrete as it might be surmised to impact the concrete's ability to restrict the passage of chloride or other ionic species. This concrete property is an important factor that affects its durability with respect to corrosion of reinforcing steel but can also impact other durability properties as affected by the transport of moisture or chemical species into the concrete.

The rapid indication of chloride ion penetrability, or also called the Rapid Chloride Permeability (RCP) test, was conducted in accordance with ASTM C 1202. Two 4 x 8 specimens were prepared for the C 1202 test. The specimens were cured in a moist room at 70 ºF until the test age. The top 2-inch portion of the test specimen as cast was used for the test. The charge passed result reported is the average of two specimens tested at the same age. Commercially available equipment as shown in Figure 2 conforming to the requirements of ASTM C 1202 was used to obtain the measurements.

The Rapid Migration test (RMT) is a provisional AASHTO standard (2004), AASHTO TP 64. This test is similar to ASTM C 1202 in that the chloride ions are driven into the concrete by an electric current. The RMT has more advantages over the C 1202 test as it is not influenced by strong ionic pore solution or admixtures such as calcium nitrite. In addition for higher permeability concretes (>1500 coulombs) the temperature in the specimen does not increase as typically observed in RCPT specimens. This means that for those concrete mixtures RMT test results provide a better indicator for ionic transport than the RCPT results in which the charge passed is exaggerated due to the high temperature. Two 4 x 8 cylindrical specimens were cured in the moist room at 70 ºF until the test age. The top 2-inches of the cylinders were cut and used for the test. A constant voltage is applied to the test specimen for a period of 18 hours. The specimen is then fractured along a diameter and sprayed with silver nitrate solution. Silver nitrate reacts with the chloride ion to provide a visible depth of penetration of the chlorides (turns white) during the test. The depth of penetration of chlorides is measured at several locations and averaged. Figure 3 illustrates the depth of penetration for a typical test specimen. The results are reported as rate of penetration in mm/(V.h), which is calculated by dividing the depth of penetration (mm) by the product of applied voltage (V) and the test duration (h). RMT results reported are the average of two specimens.

The Sorptivity test was standardized as an ASTM test method, C 1585 in 2004. In this test 2-inch thick concrete slices from a cylinder are placed with the exposed surface immersed in water as shown in Figure 4. The other surfaces of the specimen are sealed with an epoxy. The increase in specimen mass with time due to moisture absorption is measured. The initial and secondary rate of water absorption is calculated in accordance with the test procedure. Sorptivity is not a direct measure of permeability but measures the rate of flow of fluid due to capillary suction. The sorptivity of concrete is affected by the quality of the paste with respect to its porosity at the time of test. Factors such as curing also impact the sorptivity of concrete. The sorptivity test specimens were moist cured for a period of 38 days for the ACI 318 mixtures and 51 days for the HPC Bridge deck mixtures. This was followed by a period of sample conditioning as required in ASTM C 1585. The difference in moist curing ages between the 2 sets of mixtures was because of scheduling, and not any technical reason. Two cylinders were tested for each mixture and the results averaged. The sorptivity test measures the rate of absorption of water and the results is expressed in units of $mm/s^{1/2}$.

The bulk diffusion test is a new test, ASTM C 1556, standardized in 2003. In this test, after 28 days of moist curing the top 3 inches of the concrete cylinders are cut, sealed (except for the finished surface) and vacuum saturated in saturated calcium hydroxide solution. The saturated test specimen is immersed in a sodium chloride solution with one unsealed face exposed to the solution until the specimens attained an age of about 180 days. This is shown in Figure 5. The specimen was then removed and ground in 2 mm thick layers from the exposed surface. The acid soluble (total) chloride content is measured at different depths from which an apparent chloride diffusion coefficient is calculated in accordance with ASTM C 1556. The chloride diffusion coefficient is “apparent” because no corrections are made for chloride binding within the cement hydration products that would not be available to initiate corrosion. The acid soluble chloride content was measured using the rapid equipment supplied by the manufacturer and does not involve titration. The manufacturer of this equipment (Germann Instruments) has documented equivalency of results to the standard chloride measurements by ASTM C 1152. The apparent chloride diffusion coefficient is used in service life predictive models such as Life 365™ to estimate the service life of concrete structures exposed to chlorides. For the chloride diffusion, the top 2-inches of one of the 4 x 8 cylinders was tested. This is a detailed test procedure requiring in excess of 10 hours/specimen. Duplicate specimens of two of the mixtures were tested to verify repeatability.

Case 1: Concrete Floor Slab

The main features of the concrete floor slab specification used by one of the nation's largest retailer's are as follows:

a. Specified 28 day compressive strength (f'_c) =4000 psi; a required over design of 1200 psi, the required average strength (f'_{cr}) will be 5200 psi
b. Maximum water to cement ratio of 0.52. Water content to be measured by microwave oven test to estimate the w/cm – Penalties for higher w/cm and concrete rejected with a w/cm higher than 0.55
c. No fly ash or slag is allowed
d. Maximum Slump = 4 inches
e. Non air entrained concrete
f. Combined aggregate gradation shall be 8% - 18% retained on each sieve below the top size and above the No. 100 sieve. Maximum aggregate size will be 1½ inch
g. No high range water reducing admixture allowed

The performance criteria targeted the following requirements:

a. Specified 28 day compressive strength (f'_c) =4000 psi; Required average strength (f'_{cr}) based on ACI 318 or ACI 301 from past test records
b. Supplementary cementitious materials may be used
c. Slump = 4 – 6 inches
d. Length Change (drying shrinkage) (ASTM C 157) < 0.04% at 28 days of drying after 7 days of moist curing.
e. Setting time (ASTM C 403) under laboratory conditions = $5 \pm 1/2$ hours

Mixture Proportions

Five concrete mixtures were cast. The experimental variables, mixture proportions and test results are provided in Table 3. All mixtures were non-air entrained and the water content was adjusted to achieve the target slump requirement. No water reducing admixtures were used in these mixtures as initial trials with water reducing admixtures resulted in high air contents. It was felt that eliminating the use of water reducers in all mixtures would not affect the general conclusions of the study.

Mixture FS-1 is the control mixture designed according to the prescriptive specification. The 8-18 aggregate gradation specification was achieved by combining an ASTM C 33 No. 467 aggregate with a small amount of No. 8 aggregate. The specification also requires that the w/cm will be measured by the micro-wave oven test and concrete accepted based on the measured w/cm. It is anticipated that the concrete producer would have to target a lower w/cm ratio to allow for the variability of the measured water content using the microwave oven test (AASHTO T 318). The target w/cm for mixture FS-1 was set at 0.49 compared to the maximum limit of 0.52. This lower target w/cm was selected arbitrarily based on the estimate of the testing variability of AASHTO T 318 and from NRMCA field studies. Standard deviation of w/cm measurements from several batches is not published. To achieve this w/cm with the aggregates available, a higher cement content of 611 lbs/yd^3 was necessary.

Mixtures FS-2 to FS-5 were designed to satisfy the performance based criteria.

- Mixture FS-2 was similar to Mixture FS-1 except that it had a lower cement content at 517 lbs/yd^3 and thus a higher w/cm (0.57). In this case it is assumed that the producer is not restricted by a prescriptive w/cm requirement. This mixture was targeted to achieve an average strength of 4600 psi assuming that the producer has prior test records that would reduce his required average strength in accordance with ACI 318 and 301. The aggregates used in this mix were the same as in FS-1.
- Mixture FS-2R was a replicate of Mixture FS-2 repeated on a different day to establish the batch to batch repeatability of the study.
- Mixture FS-3 had 20% ASTM C 618 Class F fly ash and the total cementitious content at 530 lbs/yd^3. The aggregates used in this mix were the same as in FS-1
- Mixture FS-4 was similar to Mixture FS-3 except that the aggregate gradation did not meet the prescriptive 8-18 grading specification. The intermediate size No. 8 aggregate was not used. The combined grading of the No. 467 coarse aggregate and fine aggregate were found to be just out of range of the 8-18 grading. To further exaggerate the effect, additional coarse aggregate between the ¾ and ½ inch was added to the coarse aggregate portion of the mix.
- Mixture FS-5 was identical to Mixture FS-4 except that it was a ternary mix with Class F fly ash (15%) and slag (20%) as part of the total cementitious content.
- Figure 6 shows the combined aggregate gradations of the five mixtures tested, along with the 8-18 grading requirement.

Discussion of Test Results

The test results are provided in Table 3. Note that in this series of mixtures the water content was varied to achieve a target slump of 4 – 6 inches. The air content varied between 1.8% and 2.7% and the fresh concrete temperature varied between 66 ºF and 70 º F. The density of the concrete varied between 150.5 lb/ft^3 and 152.5 lb/ft^3. The improved workability due to the use of fly ash (relatively similar slump at 5.1% lower water content) was visibly noticeable when comparing Mixture FS-2 and Mixture FS-3.

Initial Setting Time: The setting time of mixture FS-1 was 4:12 hours, that was modestly faster than that of the other mixtures. The target concrete initial setting time of $5 \pm 1/2$ hours was met by all the performance based mixtures except Mixture FS-5 which contained both fly ash and slag and had an initial setting time of 5:59 hours which failed the performance criteria. However, this delayed setting time is not too significant relative to that of the other batches and can be rectified with some mixture adjustments to satisfy the needs of the contractor.

Finishability and Segregation: The Slab Finishability test results show that all 5 concrete mixtures had a rating above 4.5 thus indicating excellent finishability. This is a subjective test but it was clearly obvious to those working with the concrete that not much difference could be observed between the 5 concrete mixtures tested. In the Segregation test the difference in the coarse aggregate content was consistently about 20% except for Mixture FS-5 which was about 15%. This suggests that the aggregate grading differences of the mixtures within the scope of this study did not impact the segregation characteristics of the mixtures even at high slumps.

Compressive Strength: All concrete mixtures met the acceptance criteria for a specified 28-day compressive strength of 4000 psi. The compressive and initial setting times of all the mixtures is shown in Figure 7. For Mixture FS-1, the lower w/cm resulted in a compressive strength close to 5900 psi. This significantly exceeded the required average strength of 5200 psi. This illustrates a point that trying to control the acceptance criteria on w/cm forces a higher strength that is not needed for the application. This mixture also has a higher material cost to no benefit. For the performance-based mixtures, the average strength exceeded the target 4700 psi, which would be the required average strength based on a past test record with a standard deviation less than about 500 psi. The over design factor of 1200 psi as a default requirement of the specification is not necessary as it assumes a poor level of performance quality and penalizes concrete producers who practice good quality control by monitoring the performance of their mixtures.

Drying Shrinkage: The target length change (ASTM C 157) limit for the performance-based mixtures of 0.04% after 28 days of drying was achieved by all the mixtures. A surprising result was the higher length change of Mixture FS-2 as compared to Mixture FS-1 even though it had a lesser cement content (94 lbs/yd^3) and a lower paste content (1.95%). Similar mixtures tested at the laboratory around the same time did not show much change in shrinkage values. For some reason for those trials reported here the Mixture FS-1 had a higher expansion during the first 7-day moist curing period. If that high expansion is discounted then Mixture FS-1 has the same length change as Mixture FS-2 during the drying phase of the test. The comparison of Mixture FS-3 and Mixture FS-4 results show that not complying with uniform aggregate grading as intended by the 8 – 18 grading requirement does not adversely impact the length change results. In fact Mixture FS-4 which had the non uniform aggregate grading had the lowest length change values recorded of all 5 mixtures. It is presumed here that higher length change will result in increased curling of the floor slab.

Rapid Chloride Permeability: The 180 day RCP test was carried out at an age of 197 to 206 days except for Mixture 5 which was tested at an age of 174 days due to scheduling problems. The Rapid Chloride Permeability of all the mixtures is shown in Figure 8. Mixtures FS-1, and FS-2 had a chloride ion penetrability of about 3000 coulombs and hence these mixtures would be classified as having a "Moderate" chloride ion penetrability according to Table 1 of ASTM C 1202. Mixture FS-3, FS-4, and FS-5 had chloride ion penetrability of about 600 coulombs and would be classified as having "Very Low" chloride ion penetrability. Rapid chloride penetrability is typically not a desired performance requirement for concrete floor applications. Comparing the performance of Mixtures FS-3 and FS-4 indicates that the aggregate grading did not have much impact on the chloride ion penetrability.

The above experimental study brings out the following conclusions:

1. Prescriptive specifications do not essentially ensure good performance. Conforming to a uniform aggregate grading in this study did not have significant impact on the segregation, finishability or drying shrinkage of the concrete. A more extensive study focused on the effectiveness of uniform aggregate gradation is ongoing at the NRMCA Research Laboratory. Specifying a strength overdesign of 1200 psi, and establishing a w/cm ratio acceptance criteria that forces a lower target, results in a mixture (FS-1) that could in fact adversely impact

intended performance. Prohibiting the use of supplementary cementitious materials does not really protect the owner unless there is a specific technical reason. Generally this specification clause is invoked because of the perception of retarded setting or finishing problems related to slower rate of bleeding. These factors can be controlled either in the mixture development phase or by change of construction practice. The fly ash mixes have a lower water demand and the mixtures with fly ash and slag have improved workability, besides resulting in a lower permeability.

2. Another analysis that can be conducted here is the relative materials cost of the concrete mixture. Using estimates of concrete ingredient material costs from the NRMCA Industry Data Survey, it is estimated that the performance-based concrete mixtures will have a reduced materials cost between 9% and 15 % compared to that of the control Mixture FS-1. Cost savings will be higher if one considers the elimination of the use of the intermediate size No. 8 aggregate needed to achieve the 8-18 aggregate grading.

Case 2: High Performance Concrete (HPC) Bridge Deck

The main features of the high performance concrete bridge deck specification used by one Department of Transportation is as follows:

a. Specified 28 day compressive strength (f'_c) =4000 psi; Required average strength (f'_{cr}) will be based on a historical test record in accordance with ACI 318 or ACI 301.
b. Maximum water to cementitious ratio of 0.39
c. Total Cementitious Content = 705 lbs/yd^3. Cementitious composition should be at 15% fly ash and 7% to 8% silica fume
d. Slump = 4 – 6 inches
e. Air entrainment of 4% to 8% required

The performance criteria were established to target the following requirements:

a. Specified 28 day compressive strength (f'_c) =4000 psi; Required average strength (f'_{cr}) based on ACI 318 or ACI 301 using past test records
b. Supplementary cementitious materials are allowed and their quantities will not exceed limits of ACI 318 to protect against deicer salt scaling
c. Slump = 4 – 6 inches
d. Air entrainment of 4% to 8% required
e. RCPT (ASTM C 1202) = 1500 coulombs after 45 days of moist curing
f. Length Change (drying shrinkage) < 0.04% at 28 days of drying after 7 days of moist curing

Mixture Proportions

Four concrete mixtures were cast. The experimental variables, mixture proportions and test results are provided in Table 4 below. All mixtures were designed for the slump and air content requirement. All 4 mixtures contained a standard ASTM C 494 Type A water reducer dosage at 4 oz/cwt and an ASTM C 494 Type F HRWR dosage sufficient to attain the desired slump.

- Mixture BR-1 is the control mixture designed according to the DOT's prescriptive specification. The w/cm was 0.39 and the total cementitious content was 705 lbs/yd^3 out of which 15% was Class F fly ash and 7% was silica fume.

Mixtures BR-2 to BR-4 were designed to satisfy the performance based criteria. The decreased cementitious and water contents in the performance mixtures were balanced by increased aggregate contents while maintaining the same coarse to fine aggregate ratio.

- Mixture BR-2 had the same w/cm (0.39) as Mixture BR-1 but had a much lower total cementitious content (600 lbs/yd^3 as opposed to 705 lbs/yd^3). The silica fume content was set at 4% and the quantity of Class F fly ash was increased to 25% by mass of cementitious materials.
- Mixture BR-3 had the same w/cm (0.39) as Mixture BR-1 but had a much lower total cementitious content (600 lbs/yd^3 as opposed to 705 lbs/yd^3). This mixture contained 50% slag by mass of cementitious materials without silica fume or fly ash.
- Mixture BR-4 was similar to Mixture BR-2 with the replacement of Ultra Fine Fly Ash (UFFA) instead of silica fume. Based on supplier's recommendations the quantity of the UFFA was higher than that of silica fume (about 40%) at the same cement and fly ash contents. The water content of this mixture was about 7% lower than Mixture BR-2 while achieving the target slump. This reduced the w/cm of this mixture to 0.36.

Discussion of Test Results

The test results are provided in Table 4. The slump of the four mixtures varied between 4 in. and 5.75 in. The air contents varied between 4.6% and 7.6% and the fresh concrete temperature varied between 65 ºF and 69 º F. The density of the concrete varied between 144.1 lb/ft^3 and 150.5 lb/ft^3. The required ASTM Type F HRWR dosage was about 27% lower for Mixture BR-2 compared to Mixture BR-1 even at a lower water content of the concrete by over 15%. This is because of the much lower silica fume content and higher fly ash content used in Mixture BR-2. The HRWR dosage required for Mixture BR-3 was about 40% higher than that of Mixture BR-1. The required HRWR dosage was about 15% lower for Mixture BR-4 as compared to Mixture BR-1 even with a water content that was reduced by over 20%.

Compressive Strength: The specified 28-day compressive strength of 4000 psi was easily achieved and significantly exceeded by all the concrete mixtures.

Drying Shrinkage: The specified length change (ASTM C 157) of 0.04% after 28 days of drying was achieved by all the mixtures. The highest level of shrinkage (0.037%) was observed for the mixture that complied with the prescriptive HPC Bridge specification – BR-1. The 180 day drying shrinkage results are shown in Figure 9. The length change value of all the performance mixtures (BR-2, BR-3, BR-4) was much lower at all ages most likely because of the lower paste content (4.36% to 5.17%).

Rapid Chloride Permeability and Rapid Migration: The specified RCP test (ASTM C 1202) value of 1500 coulombs after 45 days of moist curing was achieved by all the mixtures except for the prescriptive BR-1 mixture which had a slightly higher value of 1563 coulombs. Note that this is still a low value of charge passed. The RCP test values after 180 days of moist curing varied between 242 and 375 coulombs which indicates a "Very Low" permeability for all mixtures.

The RMT results show that the measured rate of penetration for the mixtures after 180 days of moist curing varied between 0.0045 mm/V-hr and 0.0058 mm/V-hr. These numbers indicate no significant differences between the concrete mixtures. The results comply with the performance requirements of FHWA's HPC Grade 3 (highest durability) according to guidance provided in AASHTO TP 64. The RCPT and RMT results at two different ages are shown in Figure 10. It is useful to see that the RCPT and the RMT correspond with each other.

Sorptivity: The Sorptivity test results show that the initial rate of water absorption varied between $6.19x10^{-4}$ mm/s$^{1/2}$ and $15.20x10^{-4}$ mm/s$^{1/2}$. The prescriptive mixture had the lowest initial rate of water absorption. The performance mixtures which contained lesser or no silica fume had higher initial rate of water absorption. The final rate of water absorption varied between $3.47x10^{-4}$ mm/s$^{1/2}$ and $6.37x10^{-4}$ mm/s$^{1/2}$. At this point it is not clear as to what criteria apply to these data in categorizing the relative performance of the 4 mixtures evaluated. Clearly one might surmise that mixtures that show a higher rate of water absorption will absorb salt solution at a faster rate. After the surface of the concrete has reached a saturated state, the ingress of chlorides will be controlled by diffusion. Bulk of the chloride penetration up to the rebar is due to diffusion and not due to absorption. Sorptivity is not a measure of permeability. This test was included in this study to evaluate its applicability for performance based specification. The test is more applicable to evaluate in-place concrete and we do not recommend this test for use as the basis for acceptance of the quality of concrete furnished.

Chloride Diffusion: The Chloride Diffusion test results show that the apparent chloride diffusion coefficient at an age of 290 days varied between $7.81x10^{-13}$ m^2/s and $12.2x10^{-13}$ m^2/s. The mixture complying with the bridge specification, BR-1, had an apparent chloride diffusion coefficient of $12.2x10^{-13}$ m^2/s. It is clear that performance mixtures could be designed to attain lower apparent chloride diffusion coefficients. Regardless, the difference in the measured chloride diffusion coefficients is small and all 4 concrete mixtures can be classified as low permeability concrete mixtures. For example Life-365 service life modeling software assumes an apparent chloride diffusion coefficient of $47x10^{-13}$ m^2/s at an age of 290 days and $75x10^{-13}$ m^2/s at an age of 28 days for a plain portland cement concrete mixture with a w/cm of 0.39. The estimated surface chloride content at the termination of the exposure varied between 0.58% and 0.95% by wt of concrete. There is no correlation between the Sorptivity and chloride diffusion test results because the chloride diffusion test was conducted on a saturated specimen where as the Sorptivity test was conducted on an unsaturated specimen. Figure 11 shows the chloride content measured as a function of specimen depth for 2 of the mixtures – BR-3, and 318-1. It is clear that different mixtures differ in their ability to resist the ingress of chloride ions. At a depth of 20 mm from the surface the chloride contents for all the bridge deck mixtures are still below the threshold level of 1.5 lb/yd^3 for corrosion initiation.

Duplicate specimens of Mixtures BR-1 and BR-2 were tested and the within test range in the apparent chloride diffusion coefficient varied between 12% and 27% of the average. The within test range in the estimated surface chloride content varied between 25% and 44% of the average. However, it should be cautioned that the reported statistical information is based on just 2 mixtures and a much larger amount of testing would be required to derive meaningful statistical information. A more detailed discussion of the testing variability is provided later.

The above experimental study brings out the following conclusions:

1. The prescriptive DOT specification for bridge deck concrete can be significantly optimized for improved performance on drying shrinkage, strength, rapid chloride permeability, rapid migration and apparent chloride diffusion coefficient. The optimized mixtures resulted in improved workability (were less sticky) and had lesser water and reduced dosage of HRWR except for one mixture.
2. In a broad comparison of materials cost of the tested mixtures, it is observed that concrete mixtures optimized for performance had a lower materials cost between 15 and 23% compared to the control Mixture BR-1.

Case 3: ACI 318 Code Provisions

Durability provisions for buildings governed by the adopted local codes are addressed in Chapter 4 of ACI 318 Building Code for Structural Concrete. The Code addresses durability requirements for concrete exposed to freeze-thaw cycles, deicer salt scaling, sulfate resistance, protection from corrosion of reinforcing steel, and conditions needing low permeability. In all cases, the primary requirement of controlling the permeability of concrete is a maximum limit on the water to cementitious materials ratio (w/cm) along with a minimum specified strength. The scope of this part of the study was limited to comparing the performance of concrete mixtures having the same w/cm but with different cementitious materials and content with regards to permeability. Drying shrinkage measurements are also compared even though this is not a limitation in the Code.

Mixture Proportions

Four concrete mixtures were prepared with the same w/cm=0.42. The mixture proportions and test results are provided in Table 5.

- Mixture 318-1 contained 750 lbs/yd^3 of ASTM C 150 Type I portland cement.
- Mixture 318-2 contained 700 lbs/yd^3 of total cementitious content with 25% by mass of ASTM C 618 Class F fly ash. The paste content was lower by 1.16% as compared to Mixture 318-1.
- Mixture 318-3 contained 564 lbs/ yd^3 of total cementitious content with 25% by mass of ASTM C 618 Class F fly ash. The w/cm was maintained at 0.42 by using a HRWR. This helped to reduce the cement paste content by 7.24% as compared to Mixture 318-1. The reduction in paste content was compensated for by increasing the fine aggregate content.
- Mixture 318-4 was identical to Mixture 318-3 except that the reduction in paste content was compensated for largely by an increase in the total coarse aggregate content.

Discussion of Test Results

The results of the tests are summarized in Table 5. The slump of the concrete mixtures ranged between 3.75 and 6.5 inches and the air content ranged between 4.1% and 7.4%. The fresh concrete temperature varied between 65 ºF and 70 º F. The density of the concrete varied between 138.8 lb/ft^3 and 146.5 lb/ft^3. The improved workability due to the use of fly ash (1.75 in. higher slump at 6.7% lower water content) was clearly noticed when comparing Mixture 318-2 with Mixture 318-1.

Compressive Strength
The measured 28-day compressive strength varied between 5440 psi and 5950 psi while the 108 day strength varied between 6400 psi and 7920 psi. This indicates a variation even particularly in the later age compressive strength at the same w/cm. The higher later age strengths were attained by the fly ash concrete mixtures.

Drying Shrinkage
The average length change (ASTM C 157) after 180 days of drying varied between 0.064% and 0.032%. The reduction in the paste content and possibly the use of fly ash resulted in a reduction in shrinkage in Mixtures 318-2, 318-3, and 318-4 as compared to the control mixture. It is presumed that a higher length change will increase the propensity for drying shrinkage cracking.

Rapid Chloride Permeability, Rapid Migration, and Chloride Diffusion: The 180 day RCP test results varied between 2772 coulombs and 457 coulombs. By Table 1 of ASTM C 1202 it can be concluded that at the same low w/cm of 0.42 it is possible to make concrete having a "Moderate" chloride ion penetrability and a "Very Low" chloride ion penetrability.
RMT results show that the measured rate of penetration at 180 days varied between 0.030 mm/V-hr and 0.008 mm/V-hr. By the annex in AASHTO TP 64 it can be concluded that at the same low w/cm of 0.42 it is possible to make concrete meeting a FHWA "Performance Grade 1" and a FHWA "Performance Grade 3".
The Chloride Diffusion test results show that the apparent chloride diffusion coefficient at an age of 290 days varied between 13.7×10^{-13} m^2/s and 53.6×10^{-13} m^2/s. These are also very low values for the diffusion coefficient indicating good quality concretes relative to the permeability property. The estimated surface chloride content at the termination of the exposure varied between 0.79% and 1.35% by wt of concrete. At a depth of 20 mm from the surface the chloride contents for the control mixture is 6 lb/yd^3 as compared to about 2 lb/yd^3 for the other mixtures.

Sorptivity: The Sorptivity test results show that the initial rate of water absorption varied between 7.5×10^{-4} $mm/s^{1/2}$ and 16.4×10^{-4} $mm/s^{1/2}$. The control mixture had an initial rate of water absorption of 11.6×10^{-4} $mm/s^{1/2}$. The final rate of water absorption varied between 4.70×10^{-4} $mm/s^{1/2}$ and 9.46×10^{-4} $mm/s^{1/2}$ and the control mixture had a final rate of water absorption of 6.43×10^{-4} $mm/s^{1/2}$.

The above experimental study brings out the following conclusions:

1. At the same w/cm concrete performance, relative to the concrete's drying shrinkage and transport properties, can be drastically different by changing the type and quantity of cementitious materials and by using chemical admixtures. Code limitations on w/cm do not assure the owner that a concrete mixture with a low permeability will be achieved. In this study substantial variation in concrete performance was observed at the same w/cm. Even though the compressive strength had a smaller variation the drying shrinkage varied over a wide range, between 0.032% and 0.064%. The durability represented by the 180 day rapid chloride permeability values varied between 2772 coulombs and 457 coulombs and the measured rate of penetration at 180 days varied between 0.030 mm/V-hr and 0.008 mm/V-hr. The apparent chloride diffusion coefficient after about 290 days varied between 13.7×10^{-13} m^2/s

and 53.6×10^{-13} m^2/s. The use of supplementary cementitious materials (in this case fly ash) substantially influences permeability to chloride ions and durability even at the same w/cm.

2. Over the years considerable advances have been made in understanding the influence of concrete mixture optimization for concrete durability. Requirements in the ACI 318 Building Code have not kept pace with those developments. It continues to attach importance to w/cm as the primary means of controlling concrete durability. This test program shows that significant difference in durability and shrinkage can be attained at the same w/cm and similar strength levels. Alternative options for durability should be considered to the current limitations of the ACI 318 Building Code.

Evaluation of Testing Variability

The within lab single operator precision is calculated for each of the hardened concrete tests conducted in this project and shown in Table 6. This is the range percent which is the range of two results expressed as a percentage of the average of the two determinations. This range percent can be compared to the d2s value in precision statement of test methods as described in ASTM C 670. The d2s value is an acceptable difference between two determinations. Essentially the calculation of this range percent is a measure of the within test variability. Higher the range percent calculated higher the within test variability. The average range percent represents the average for all the mixtures for which that test was conducted. The maximum and minimum values of the range percent and the acceptable range percent as mentioned in the precision statement of that ASTM test procedure are also given.

The test results in Table 6 show that in all cases the measured range percent was less than the acceptable range percent (or d2s) provided by that ASTM test method. Compressive strength test results show the lowest testing variability (lowest range percent of 2.6%) followed by the RCPT (9.3% to 14.8%), shrinkage (15.1% to 19.1%), RMT (17.2% to 19.3%), sorptivity (18.7% to 27.9%), diffusion coefficient (19.3%), and surface chloride content (34.8%). In general for the same test the earlier age testing showed slightly higher variability than the later age testing. However, for the sorptivity test the secondary rate of water absorption had lower variability (18.7%) as compared to the initial rate of water absorption. RMT, diffusion coefficient, and sorptivity are fairly new tests and it is possible that the within test variabilities measured in this project may decrease as the operators get more experience. In general before requiring a test for concrete acceptance it is important to consider the variability of the test that is specified. A test method that shows a high testing variability is most likely to show a high variability at the job site. This increases the risk of rejecting acceptable product, which impacts the concrete supplier. For this reason acceptance criteria established in specifications should take into consideration the precision of the test. It is well known that the acceptance criteria for strength requirements are based on a 1% probability of failure. The acceptance criteria for a durability test such as RCPT established on a similar basis could cause a significant shift in the designed mix to avoid the potential of a failure. For example, to achieve the specified RCPT value of 1000 coulombs the concrete producer would be forced to target a much lower average RCPT value which would lead to unrealistic and expensive concrete mixtures. A better approach would be to word the specification as "80% of the specimens should be below 1000 coulombs".

In addition the batch to batch variability was measured by comparing the performance of mixtures FS-2 and FS-2B. The results show that the slump, air content, density and compressive strength did not vary by more than the precision limits suggested by ASTM C 192.

Summary

The above 3 examples of concrete floors, HPC bridge decks, ACI 318 code limitations demonstrate that:

1. Performance criteria in specifications for concrete will assure the owner that the performance objectives are achieved. Prescriptive specifications that imply performance do not assure much. In both applications studied in this project – concrete floor, and HPC bridge deck – targeting specific performance criteria resulted in equal or better performance (shrinkage, workability/lower admixture dosage, lower chloride permeability etc.) as compared to prescriptive limitations in the specification. Along with improved performance, it is envisioned that the owner will benefit from reduced costs related to optimized material use and elimination of problems during construction and the associated delay in construction schedule.
2. Performance specifications allow a great opportunity to optimize the concrete mixture designs. This ensures that different producers can compete based on their knowledge and resources and better serve the needs of the project. Prescriptive specifications typically cause a waste of resources to no benefit related to the performance of the concrete mixtures. Allowing the concrete supplier to optimize for performance brings additional benefits to the project.
3. ACI 318 w/cm limits that control intended durability need a fresh look as this test program demonstrates significant differences in performance related to permeability and shrinkage can be attained even at the same w/cm and similar strength.

Acknowledgements

The authors would like to extend their sincere thanks to Mr. Gary Mullings, Mr. Fernando Rodriguez, Mr. Haejin Kim and Mr. Soliman Ben-Barka who conducted the test program at the NRMCA Research Laboratory. The authors would like to thank the following companies for supplying materials for this project: Aggregate Industries, Boral Material Technologies, Lehigh Cement Company, and W.R. Grace. Funding for the study was provided by the RMC Research Foundation.

References

Four publications, 15 to 18 in the list below, are a result of this project funded by the RMC Research Foundation. In addition three presentations will be made at the following locations - TRB Annual Meeting in 2006, National Concrete Bridge Conference in 2006 and a presentation was already made at the P2P Steering committee meeting in October 2005. In addition the results of this study will be included as part of future P2P presentations.

1. AASHTO TP 64, "Standard Method of Test for Predicting Chloride Penetration of Hydraulic Cement Concrete by the Rapid Migration Procedure", *AASHTO*, 2004.
2. ACI 301-05, "Specification for structural concrete", *American Concrete Institute*, Farmington Hills, Michigan, USA.

3. ACI 318-05, “Building Code Requirements for Structural Concrete,” ACI Manual of Concrete Practice, *American Concrete Institute*, Farmington Hills, Michigan, USA.
4. ASTM C 1064-01, "Test method for temperature of freshly mixed portland and cement concrete", *American Society for Testing and Materials*, Pennsylvania, USA.
5. ASTM C 1202-97, "Test method for electrical indication concrete's ability to resist chloride ion penetration", *American Society for Testing and Materials*, Pennsylvania, USA.
6. ASTM C 138-01, "Test method for density (unit weight), yield and air content (gravimetric) of concrete", *American Society for Testing and Materials*, Pennsylvania, USA.
7. ASTM C 143-00, "Test method for slump of hydraulic cent concrete", *American Society for Testing and Materials*, Pennsylvania, USA.
8. ASTM C 1556-03, “Standard Test Method for Determining the Apparent Chloride Diffusion Coefficient of Cementitious Mixtures by Bulk Diffusion,” *American Society for Testing and Materials*, Pennsylvania, USA.
9. ASTM C 157-99, "Test method for length change of hardened hydraulic-cement mortar and concrete", *American Society for Testing and Materials*, Pennsylvania, USA.
10. ASTM C 1585-04, “Test Method for Measurement of Rate of Absorption of Water by Hydraulic-Cement Concretes”, *American Society for Testing and Materials*, Pennsylvania, USA.
11. ASTM C 192-02, "Practice for making and curing concrete test specimens in the laboratory", *American Society for Testing and Materials*, Pennsylvania, USA.
12. ASTM C 231-97, "Test method for air content of freshly mixed concrete by the pressure method", *American Society for Testing and Materials*, Pennsylvania, USA.
13. ASTM C 39-01, “Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens,” *American Society for Testing and Materials*, Pennsylvania, USA.
14. Lemay, L., Obla, K., and Lobo, C., “Performance Based Specifications for Concrete: A Focus on Innovation, Quality and Customer Satisfaction,” *STRUCTURE*, April 2005, pp. 22-25.
15. Obla, Karthik, Lobo, Colin, and Kim, Haejin, “Experimental Case Study Demonstrating Advantages of Performance Specifications”, NCBC Conference, May 2006.
16. Obla, Karthik and Lobo, Colin, “Laboratory Demonstration of Advantages of Performance Specifications”, Indian Concrete Journal, Vol 79, No. 12, Dec 2005, pp 22-26.
17. Obla, Karthik, “Performance-Based Specifications: Laboratory Study Demonstrating the Advantages”, Transportation Research Board, 85th Annual Meeting, Washington DC, January 2006.
18. Obla, Karthik, "Experimental Case Study Demonstrating Advantages of Performance Specifications", Concrete infocus, Summer 2005, Vol. 4, No. 2, pp. 32-42.

List of Tables

List of Figures

Table 1 Properties of Aggregate Used in Study

Sieve Size	Percent Passing			
	Coarse Aggregate			Fine Aggregate
	No.467	No. 67	No. 8	
2 1/2	100.0	100.0	100.0	100.0
2	100.0	100.0	100.0	100.0
1 1/2	99.1	100.0	100.0	100.0
1	74.5	100.0	100.0	100.0
3/4	59.3	96.5	100.0	100.0
1/2	32.3	80.0	100.0	100.0
3/8	18.2	41.9	88.3	100.0
No. 4	6.5	6.3	17.4	100.0
No. 8	0.0	2.5	2.7	87.6
No. 16	0.0	0.0	1.6	67.3
No. 30	0.0	0.0	0.0	41.9
No. 50	0.0	0.0	0.0	17.7
No. 100	0.0	0.0	0.0	10.6
No. 200	0.0	0.0	0.0	5.7
FM	7.17	6.53	5.90	2.75
Bulk Dry Specific Gravity	2.84	2.83	2.83	2.58
Absorption, %	0.30	0.3	0.3	1.1
Dry rodded unit weight, lb/ft^3	110.0	109.0	N/A	N/A

Table 2 Tests Conducted in Study

All concrete batches were tested for slump, ASTM C 143, air content, C 231, density, C 138 and temperature, C 1064. In additions the following tests were conducted.

Tests	Case 1: Floor Slab	Case 2: HPC Bridge	Case 3: ACI 318
Compressive Strength	√	√	√
Initial Setting Time	√		
Finishability Index	√		
Segregation	√		
Shrinkage	√	√	√
Rapid Chloride Permeability	√	√	√
Rapid Migration		√	√
Bulk Chloride Diffusion		√	√
Sorptivity		√	√

Table 3 Details of Floor Slab Mixtures

Mixture	Experimental Variables
FS-1	Control Mixture. f'_{cr} = 5200 psi; w/cm = 0.49; aggregate gradation meets 8-18 limits; no fly ash or slag; total cementitious = 611 lb/yd^3
FS-2	f'_{cr} = 4600 psi; w/cm = 0.57; total cementitious = 517 lb/yd^3
FS-3	f'_{cr} = 4600 psi; w/cm = 0.57; 20% Class F fly ash; total cementitious = 530 lb/yd^3
FS-4	f'_{cr} = 4600 psi; w/cm = 0.57; two aggregates – does not comply with 8-18 limits; total cementitious = 530 lb/yd^3
FS-5	f'_{cr} = 4600 psi; w/cm = 0.57; 15% Class F fly ash; 20% slag; two aggregates – does not comply with 8-18 limits; total cementitious = 530 lb/yd^3

	FS-1	FS-2	FS-2R	FS-3	FS-4	FS-5
Calculated mixture proportions, lb/yd^3						
Cement	614	515	521	423	424	343
Fly Ash	0	0	0	106	106	79
Slag	0	0	0	0	0	105
Total Cementitious Content	614	515	521	529	530	527
Coarse Agg #1 (#467)	1740	1725	1744	1725	1811	1803
Coarse Agg #2 (#8)	307	305	308	305	0	0
Coarse Agg #3 (1/2"-3/4")	0	0	0	0	224	223
Fine Aggregate	1157	1224	1237	1225	1230	1223
Water	299	294	297	279	280	287
w/cm	0.49	0.57	0.57	0.53	0.53	0.54
Fresh Concrete Properties						
ASTM C 143, Slump, in.	4.00	4.75	4.50	6.00	4.75	5.50
ASTM C 231, Air, %	1.8	2.0	1.6	2.7	2.3	2.7
ASTM C 138, Density, lb/ft^3	152.5	150.5	152.1	150.5	150.9	150.5
ASTM C 1064, Temp., ºF	71	70	67	68	66	70
ASTM C 403 Initial Setting Time, h:m	4:12	4:45		5:30	5:17	5:59
Final Setting Time, h:m	5:55	6:20		8:02	7:26	8:28
Finishability Index (1-5)	4.75	4.50		4.50	5.00	4.50
Hardened Concrete Properties						
ASTM C 39, Compressive Strength, psi						
3 days	3,480	2,820		2,250	2,820	1,630
7 days	4,420	3,740	3,560	3,100	3,210	2,800
28 days	5,870	5,050	5,150	4,860	4,980	4,720
ASTM C 157, Length Change, %						
28 days	-0.018%	-0.020%		-0.014%	-0.016%	-0.035%
90 days	-0.032%	-0.045%		-0.031%	-0.026%	-0.040%
180 days	-0.037%	-0.046%		-0.027%	-0.027%	-0.042%
Segregation						
Top to bottom Diff. in CA, %	22.2%	24.0%		21.5%	23.3%	15.0%
ASTM C 1202, "Rapid Chloride Permeability", Coulombs						
80 days	2709	4520		3093	2726	839
200 days	3050	3067		538	635	584

Table 4 Details of the HPC Bridge Deck Mixtures

Mixture	Experimental Variables
BR-1	Control Mixture. w/cm = 0.39; 15% Class F fly ash; 7% silica fume; total cementitious = 705 lb/yd^3
BR-2	w/cm= 0.39; 25% Class F fly ash; 4% silica fume; total cementitious = 600 lb/yd^3
BR-3	w/cm= 0.39; 50% slag; total cementitious = 600 lb/yd^3
BR-4	w/cm= 0.36; 25% Class F fly ash; 5.6% ultra-fine fly ash; total cementitious = 600 lb/yd^3

	BR-1	BR-2	BR-3	BR-4
Calculated mixture proportions, lb/yd^3				
Cement, lb/yd^3	556	420	307	412
Fly Ash, lb/yd^3	106	148	0	145
Silica Fume, lb/yd^3	51	24	0	0
Slag, lb/yd^3	0	0	307	0
UFFA, lb/yd^3	0	0	0	33
Total Cementitious Content, lb/yd^3	713	591	614	590
Coarse Aggregate (#67) , lb/yd^3	1820	1894	1985	1881
Fine Aggregate, lb/yd^3	1133	1182	1237	1174
Water, lb/yd^3	278	231	239	211
w/cm	0.39	0.39	0.39	0.36
AEA (oz/cwt.)	0.40	0.45	0.40	0.40
Type A WR (oz/cwt.)	4	4	4	4
Type F HRWR (oz/cwt.)	13.0	9.4	18.4	11.1
Fresh Concrete Properties				
ASTM C 143, Slump, in.	4.00	5.00	5.00	5.75
ASTM C 231, Air, %	4.6	7.2	4.7	7.6
ASTM C 138, Density, lb/ft^3	145.7	144.1	150.5	142.5
ASTM C 1064, Temp., ºF	69	69	65	69
Hardened Concrete Properties				
ASTM C 39, Compressive Strength, psi				
3 days	4,150	3,650	2,600	3,710
7 days	5,420	4,880	5,560	5,160
28 days	7,480	6,800	8,970	7,180
ASTM C 157, Length Change, %				
28 days	-0.037%	-0.017%	-0.021%	-0.018%
90 days	-0.045%	-0.027%	-0.029%	-0.027%
180 days	-0.043%	-0.024%	-0.025%	-0.024%
ASTM C 1202, “Rapid Chloride Permeability”, Coulombs				
45 days	1563	1257	1126	1244
110 days	541	434	541	479
180 days	327	275	375	242
AASHTO TP 64 “Rapid Migration Test”, mm/(V-hr)				
60 days	0.019	0.018	n/a	0.023
120 days	0.0090	0.0070	0.0060	0.011
180 days	0.0058	0.0045	0.0054	0.0047
ASTM C 1585, Rate of Water Absorption (Sorptivity) at 69 days, x10^{-4} mm/s$^{1/2}$				
Initial	6.19	7.37	8.89	15.20

Secondary	3.47	4.59	4.52	6.37
ASTM C 1556, Diffusion Coefficient, x10^{-13} m^2/s				
140 days	21.9	17.9	15.4	34.2
290 days	12.2	11.1	7.81	11.5
ASTM C 1556, Surface Chloride, % by weight of concrete				
140 days	0.90	0.95	0.58	0.67
290 days	0.97	0.92	1.10	0.98

Table 5 Details of the ACI 318 Mixtures

Mixture	Experimental Variables
318-1	Control Mixture. w/cm = 0.42; portland cement only = 750 lb/yd^3
318-2	w/cm = 0.42; 25% Class F fly ash; total cementitious = 700 lb/yd^3
318-3	w/cm = 0.42; 25% Class F fly ash; total cementitious = 564 lb/yd^3
318-4	w/cm = 0.42; 25% Class F fly ash; total cementitious = 564 lb/yd^3; coarse agg. increased by 12%

	318-1	318-2	318-3	318-4
Calculated mixture proportions, lb/yd^3				
Cement, lb/yd^3	727	540	419	416
Fly Ash, lb/yd^3	0	180	140	139
Total Cementitious Content, lb/yd^3	727	720	558	555
Coarse Aggregate (#67) , lb/yd^3	1746	1852	1781	1989
Fine Aggregate, lb/yd^3	975	1086	1314	1111
Water, lb/yd^3	303	299	233	231
w/cm	0.42	0.42	0.42	0.42
AEA (oz/cwt.)	0.35	0.39	0.49	0.39
Type A WR (oz/cwt.)	4	4	4	4
Type F HRWR (oz/cwt.)	0	0	7.4	9
Fresh Concrete Properties				
ASTM C 143, Slump, in.	4.75	6.5	3.75	5.25
ASTM C 231, Air, %	7	4.1	7.2	7.4
ASTM C 138, Density, lb/ft^3	138.8	146.5	143.7	143.7
ASTM C 1064, Temp., ºF	70	69	67	65
Hardened Concrete Properties				
ASTM C 39, Compressive Strength, psi				
3 days	3,800	3,610	3,220	3,110
7 days	4,270	4,330	4,060	4,020
28 days	5,440	5,950	5,670	5,600
108 days	6,400	7,920	6,740	7,420
ASTM C 157, Length Change, %				
28 days	-0.048%	-0.034%	-0.029%	-0.024%
90 days	-0.064%	-0.048%	-0.039%	-0.033%
180 days	-0.064%	-0.048%	-0.037%	-0.032%
ASTM C 1202, "Rapid Chloride Permeability", Coulombs				
28 days	8356	5610	4462	4036
120 days	3421	1181	996	835
180 days	2772	608	533	457
AASHTO TP 64 "Rapid Migration Test", mm/(V-hr)				
50 days	0.069	0.042	0.049	0.037
120 days	0.037	0.016	0.017	0.016
180 days	0.030	0.0077	0.015	0.0082
ASTM C 1585, Rate of Water Absorption (Sorptivity) at 56 days, x10^{-4} mm/s$^{1/2}$				
Initial	11.6	16.4	7.51	11.4
Secondary	6.43	9.46	4.72	4.70

ASTM C 1556, Diffusion Coefficient, x10^{-13} m^2/s				
210 days	49.6	28.7	26.1	25.8
290 days	53.6	13.7	30.6	18.9
ASTM C 1556, Surface Chloride, % by weight of concrete				
210 days	0.98	1.19	0.72	0.74
290 days	0.87	1.35	0.79	0.85

Table 6 Testing Variability

Test Procedure	Range, %			ASTM d2s limits, %
	Average	Maximum	Minimum	
Compressive strength, 28 days	2.6%	6.2%	0.1%	6.6%
Shrinkage				
28 days	19.1%	50.9%	0.0%	125.0%
180 days	15.1%	41.3%	0.0%	125.0%
RCPT				
35 days	14.8%	29.1%	3.4%	42.0%
180 days	9.3%	27.1%	0.5%	42.0%
RMT				
55 days	19.3%	22.2%	0.0%	42.0%
180 days	17.2%	34.4%	2.3%	42.0%
Sorptivity, 56 days				
initial	27.9%	72.4%	14.3%	N/A
secondary	18.7%	48.4%	5.2%	N/A
Diffusion Coefficient, 180 days	19.3%	n/a	n/a	39.8%
Surface Chloride, 180 days	34.8%	n/a	n/a	37.2%

Figure 1 Finishability Test in Progress

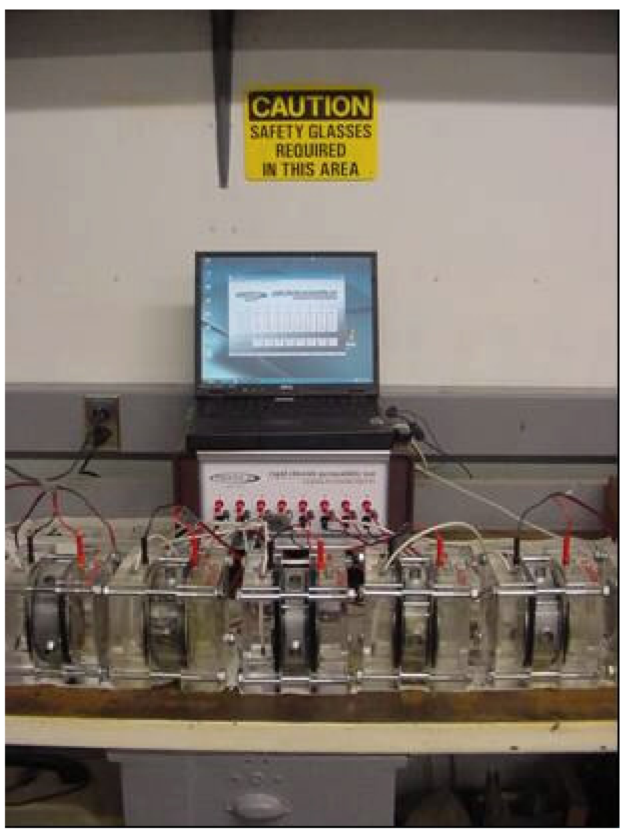

Figure 2 Rapid Indication of Chloride Ion Penetration (ASTM C 1202) Test Set Up

Figure 3 Rapid Migration Test (AASHTO TP 64) Showing Chloride Penetration Depths

Figure 4 Sorptivity Test (ASTM C 1585) Set Up

Figure 5 Chloride Diffusion Test (ASTM C 1556) Specimens Immersed in Chloride Solutions (5 gallon bucket is covered and sealed until test age)

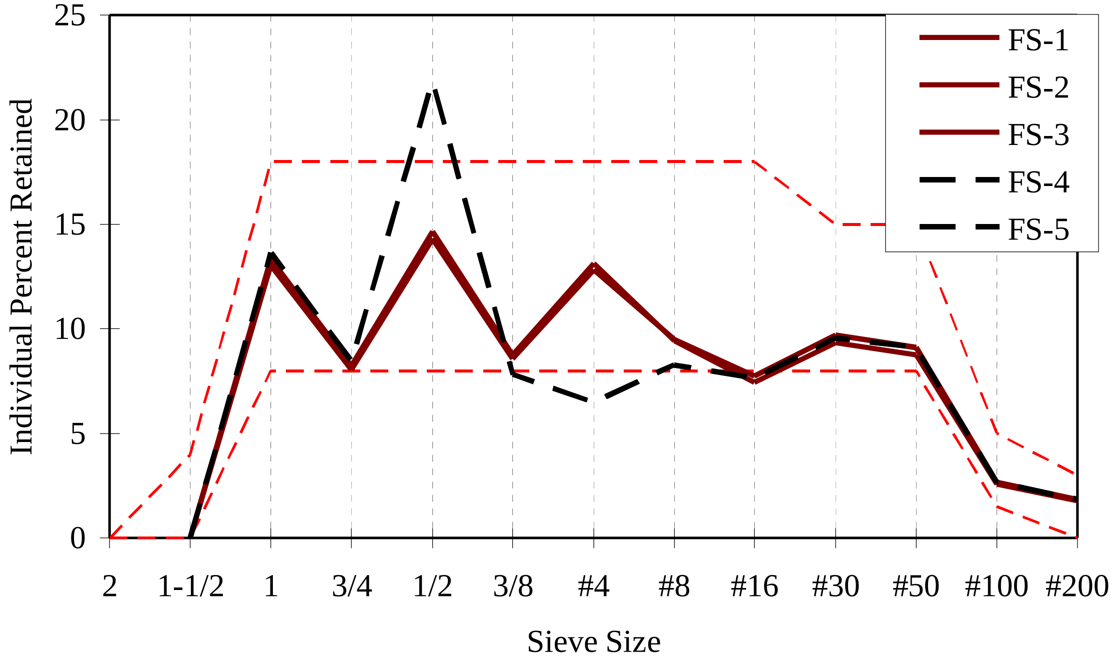

Figure 6 Combined Aggregate Grading for Floor Slab (FS) Mixtures Relative to 8-18 Criteria

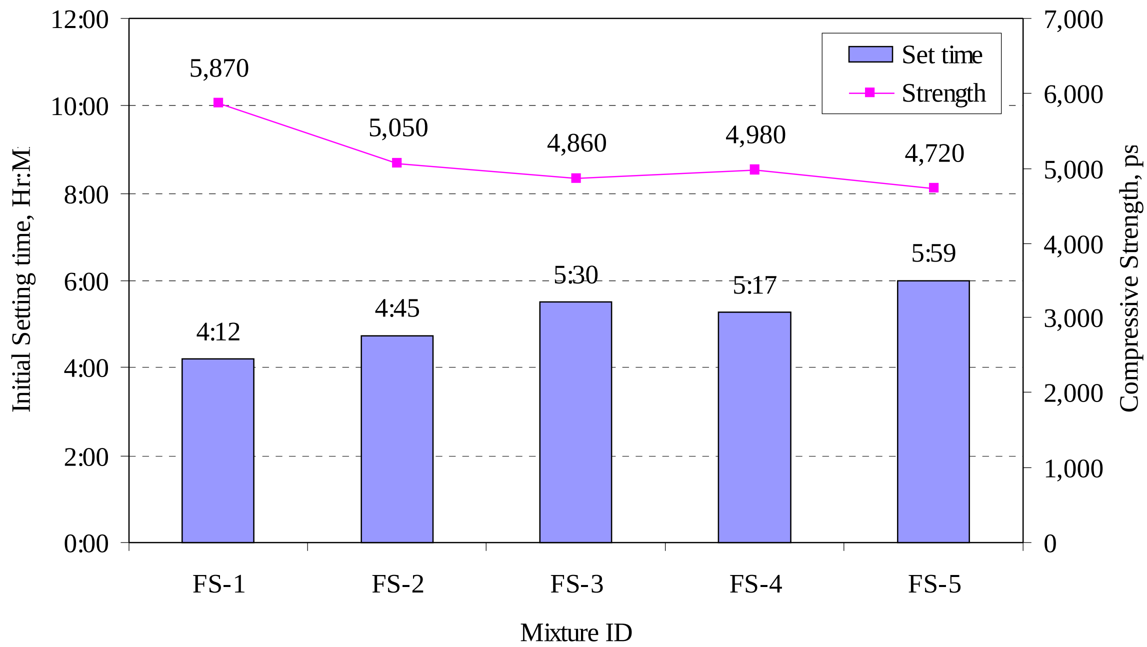

Figure 7 Strength and Setting Times of Prescriptive and Performance FS Mixtures

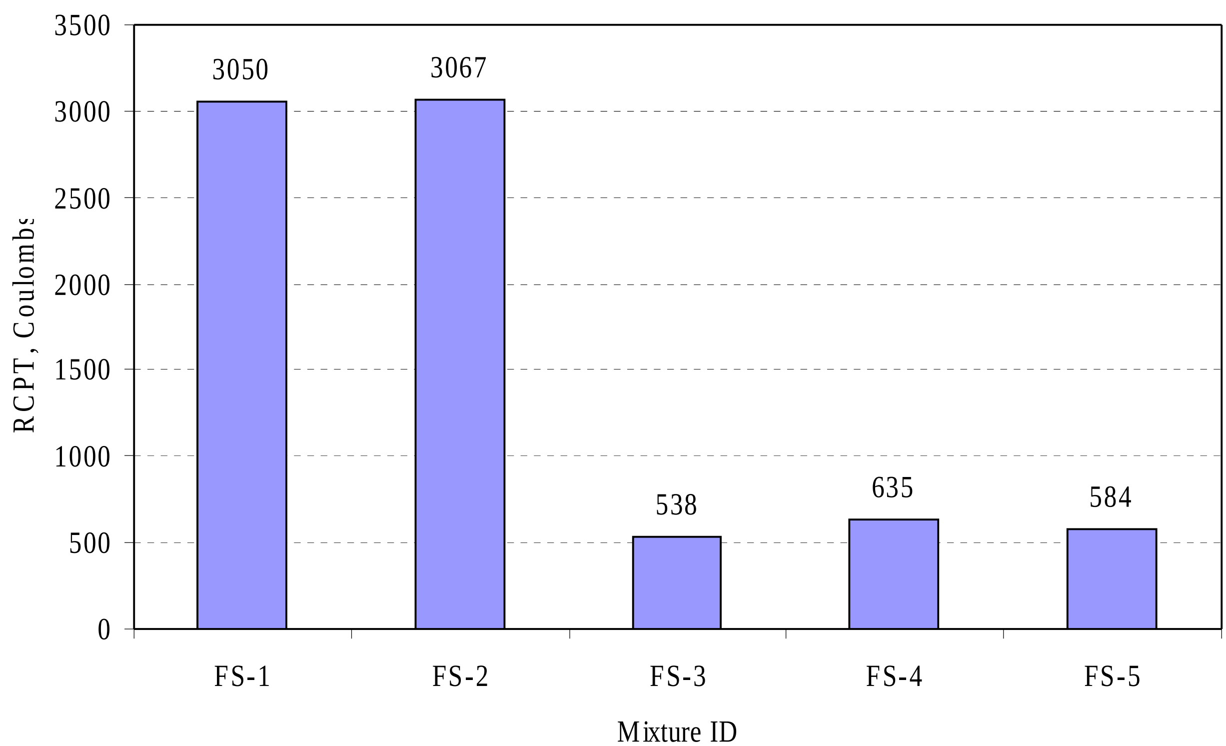

Figure 8 Durability of Prescriptive and Performance FS Mixtures

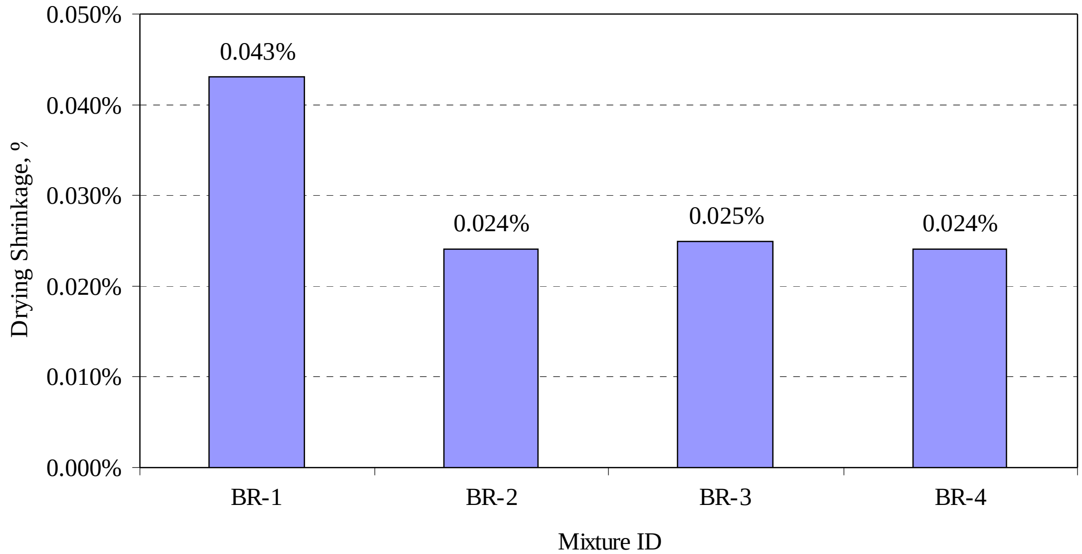

Figure 9 Drying Shrinkage of Prescriptive and Performance HPC Bridge Deck (BR) Mixtures

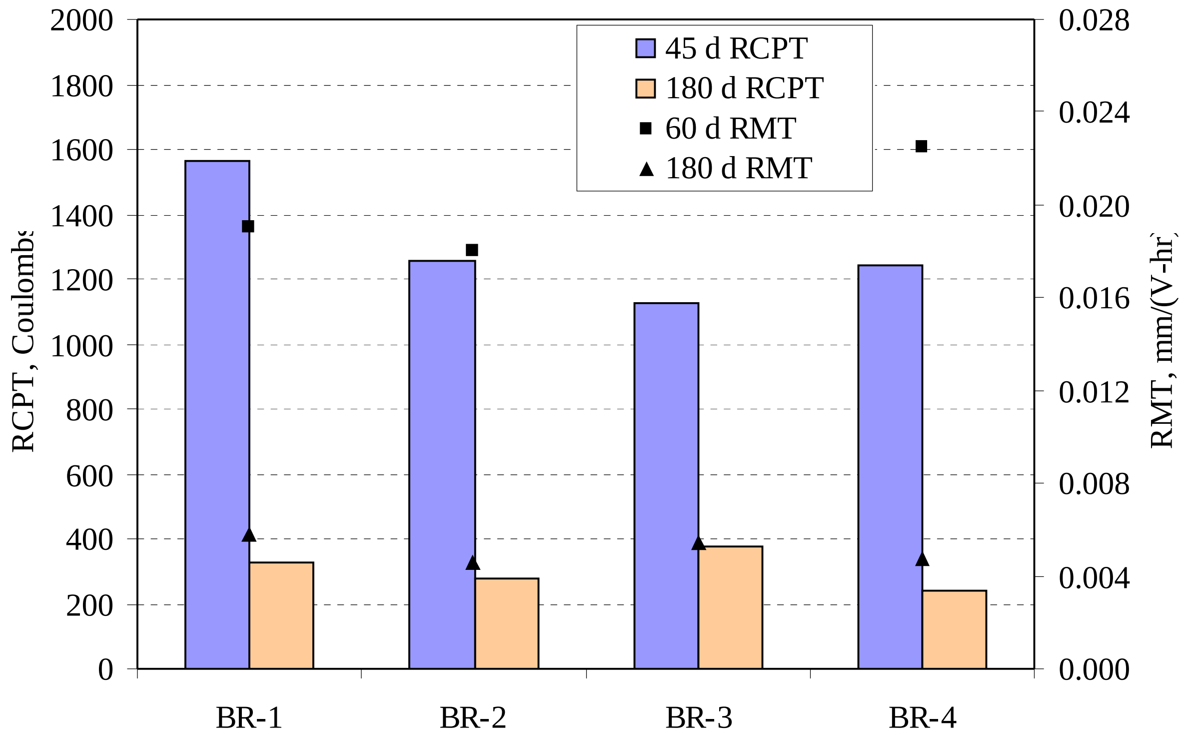

Figure 10 Chloride Ion Penetration Resistance of Prescriptive and Performance BR Mixtures

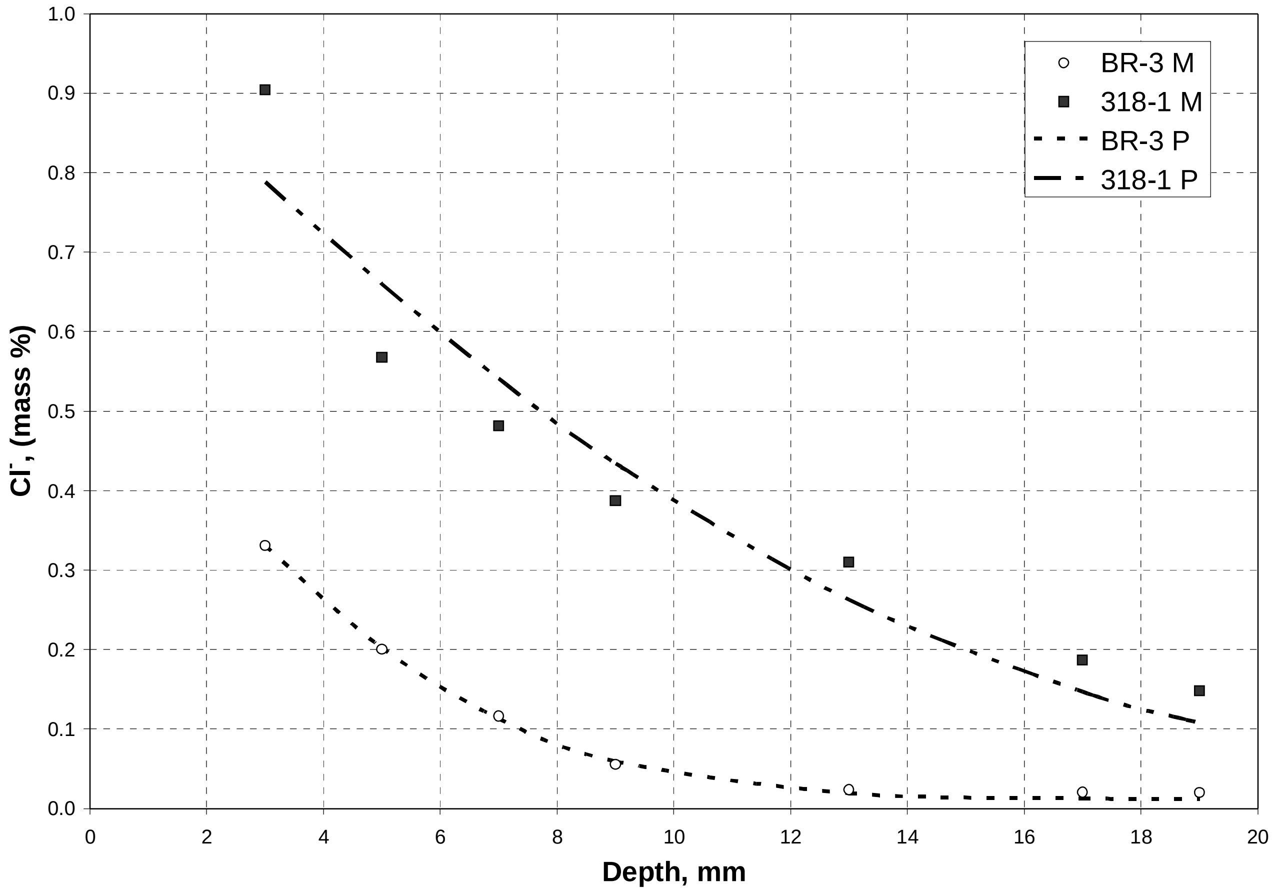

Figure 11 Chloride Penetration into Concrete Expose to Sodium Chloride Solution