VARIATION OF CONCRETE STRENGTH, PERMEABILITY, AND POROSITY DUE TO SPECIMEN TYPE, SEASON, AND AGE

By
Matthew O'Reilly
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A Report on Research Sponsored by

The Kansas Department of Transportation

K-TRAN Project KU-12-1

Structural Engineering and Engineering Materials
SM Report No. 120
January 2017

THE UNIVERSITY OF KANSAS CENTER FOR RESEARCH, INC.
2385 Irving Hill Road, Lawrence, Kansas 66045-7563

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PREFACE

The Kansas Department of Transportation's (KDOT) Kansas Transportation Research and New-Developments (K-TRAN) Research Program funded this research project. It is an ongoing, cooperative and comprehensive research program addressing transportation needs of the state of Kansas utilizing academic and research resources from KDOT, Kansas State University, and the University of Kansas. Transportation professionals in KDOT and the universities jointly develop the projects included in the research program.

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ABSTRACT

Time and curing conditions may impact the strength and permeability of concrete. The strength and permeability of concrete with and without supplementary cementitious materials (SCMs) were evaluated as a function of specimen type, season during which construction occurred, and age. Three concrete mixtures in which the cementitious material consisted of 100% portland cement, 65% portland cement and 35% slag cement, or 60% portland cement, 25% slag cement, and 15% Class C fly ash were evaluated. Pavement slabs containing each mixture were cast in the summer, fall, and spring, along with companion 4 × 8 in. cylinders, to determine the effect of seasonal variations in environmental conditions on the strength and permeability of the concrete. Cylinders were cured in both the laboratory and the field, and cores were taken from each slab. Specimens were evaluated for compressive strength, ionic conductivity using the rapid chloride permeability (RCP) test, and void content using the boil test at ages of 28, 56, 90, 180, 360, and 720 days. Equations are presented that characterize the change in strength, ionic conductivity, and porosity over time, and relationships between lab-cured cylinder values and values from field-cured cylinders and cores for compressive strength, RCP, and boil test were established.

The study demonstrates that concrete cast in moderate temperatures exhibited greater compressive strength, lower charge passed in the RCP test, and a lower percentage of voids in the boil test than concrete cast in high or low temperatures; the use of slag cement or slag cement and Class C fly ash as partial replacements for portland cement lessened the negative impact of high temperatures on these properties, but was detrimental to the early age properties of concrete cast in cold temperatures. Cores and field-cured cylinders exhibited lower compressive strength and greater ionic conductivity and voids than lab-cured cylinders. The equations developed in this report reasonably predict the change in strength, charge passed, and percentage of voids over time. No correlation was found between results from the boil test and results from the RCP test.

KEYWORDS: compressive strength, concrete, durability, ionic conductivity, porosity, supplementary cementitious materials

ACKNOWLEDGEMENTS

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This project would not have been possible without the work of graduate students Jiqiu Yuan, Scott Storm, James Lafikes, and Isaac Somogie, as well as several undergraduate assistants. Their contributions are greatly appreciated.

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CHAPTER 1: INTRODUCTION

1.1 Problem Statement

Questions have arisen in practice about the rate at which concrete systems gain strength over time and the relationship between test results from concrete cast in the field and those derived from cylinder tests. The gain in strength for concrete mixtures with and without supplementary cementitious materials and the related impact of time and curing conditions on the permeability of these mixtures are also of interest.

Concrete gains strength at different rates depending on the curing conditions and mixture constituents. The durability of concrete, as measured by its relative permeability, is also affected by the degree of hydration of the concrete mixture. The moisture available to support the hydration process and the temperature of the concrete at placement and during curing are key factors that influence the strength and permeability of the concrete over time. In addition, some combinations of supplementary cementitious materials (SCMs) and portland cement react more slowly than portland cement alone and, therefore, require different curing conditions to achieve similar strength and permeability as concrete that contains only portland cement.

1.2 Objectives and Scope

This report presents a summary of findings with regards to how concrete compressive strength, permeability, and porosity are affected by age at testing, environmental conditions, and curing methods. Three mixtures were evaluated: a control mixture with 100% portland cement, a mixture with 35% replacement (by weight) with slag cement, and a mixture with 15% replacement with fly ash and 25% replacement with slag cement. Compressive strength (ASTM C39), rapid chloride permeability (RCP)

(ASTM C1202), and boil (KT-73) tests were performed on lab-cured cylinders, field-cured cylinders, and cores. These results were used to develop predictive equations demonstrating how these material properties could be expected to vary with time and method of sampling. This report is a summary of the findings presented by O'Reilly et al. (2016).

CHAPTER 2: SUMMARY OF EXPERIMENTAL WORK

2.1 Introduction and Test Program

This chapter summarizes the materials used and casting procedure and tests performed on the slabs and cylinders cast for this project. The University of Kansas (KU) test program included three concrete mixtures with cementitious material contents of (1) 100% portland cement, (2) 35% slag and 65 % portland cement, and (3) 15% class C fly ash, 25% slag, and 60% portland cement. The aggregate gradations in the KU mixtures were optimized using the KU Mix design program: (https://iri.drupal.ku.edu/node/43).

Concrete slabs, 8-ft square and 10 in. thick, were cast in the field under three different seasonal conditions during summer 2011, fall 2011, and spring 2012. Three sets of specimens (lab-cured cylinders, field-cured cylinders, and cores from the 10-in. concrete slabs) were tested at 28, 56, 90, 180, 360, and 720 days for strength and permeability properties. Strength (ASTM C39) and boil (KT-73) tests were conducted at KU. Rapid chloride permeability tests (RCPT, ASTM C1202) were conducted at the Kansas Department of Transportation (KDOT) Research Laboratory.

2.2 Slab and Cylinder Casting Procedure

The procedure for casting the slabs followed the guidelines outlined in Section 501, Portland Cement Concrete Pavement (QC/QA), of the "Standard Specifications for State Road & Bridge Construction" (KDOT 2007). Each placement consisted of one 8 ft × 8 ft × 10 in. slab and 120 4 in. × 8 in. concrete cylinders. The slab was placed on a 4-in. thick layer of compacted AB-3 subgrade.

Upon arrival of the concrete truck, initial slump and air (pressure method) tests were performed to ensure the concrete met KDOT specifications for pavement (air between

4 and 10%, slump ≤ 4 in.) (KDOT 2007) prior to placement. Concrete samples with a volume of 5 ft^3 were collected after one-third and two-thirds of the slab had been placed. The two samples were combined and used to measure slump, temperature, and air content, and prepare the lab and field-cured cylinders. The slab was consolidated using a handheld vibrator and finished with a vibrating screed and bullfloat. A curing compound (Sealtight 1610) was applied using a pump sprayer shortly after bullfloating.

The test cylinders were 4 in. by 8 in. and were made in accordance with ASTM C31. The cylinders were numbered 1-120 and filled in numerical order by two teams, each consisting of two or three ACI Field Testing Technicians – Grade I, one starting with Cylinder 1 and the other starting with Cylinder 61. The lab-cured cylinders were stored in a shed for the first 24 hours, with ice or insulation as needed to control the air temperature adjacent to the cylinders. The field-cured cylinders were stored outdoors in a wire cage to protect them from being disturbed. The cage was located close to the slabs to ensure that the field-cured cylinders and slab experienced the same environmental conditions. Due to the nature of the wire cages, some field-cured cylinders were exposed to direct sunlight while others were partially shielded from the sun. The slab and all cylinders were demolded after 24 hours. The cylinders to be lab-cured were moved to the laboratory after 24 hours and stored in lime-saturated water until testing; the field-cured cylinders remained on site until about one week prior to testing.

2.3 Mixture Proportions

All mixtures evaluated contained Type I/II portland cement. Three mixtures were evaluated; one containing 100% portland cement, one containing a 35% replacement by weight of cement with slag cement, and one containing a 25% replacement with slag cement and a 15% replacement with Class C fly ash. Three aggregates–limestone coarse aggregate, pea gravel, and Kansas River sand–were used and proportioned using the KU Mix design program to optimize the aggregate gradations. Admixtures included W. R. Grace Adva 140 (ASTM C494, Type A and F) water reducer and Daravair 1400 air entraining agent. The nominal air content was 6.5% for all mixtures. The summer slab with 100% portland cement also included 16 oz of Daratard 17 (ASTM C494, Type B and D) as a set retarder. Mixture proportions are shown in Table 2.1.

Table 2.1: Concrete Mixture Proportions

Material	**100% PC**	**65% PC/ 35% Slag**	**60% PC/ 25%Slag/ 15% Fly Ash**
	Quantity, SSD		
Cement	520 lb	338 lb	312 lb
Slag	-	182 lb	130 lb
Class C Fly Ash	-	-	78 lb
Water	213 lb	214 lb	216 lb
Limestone	1432 lb	1432 lb	1431 lb
Pea Gravel	994 lb	978 lb	971 lb
Sand	653 lb	657 lb	658 lb
Daravair 1400	7.0 oz	6.5 oz	3.7 oz.
ADVA 140	68 oz	70 oz	44 oz

The plastic concrete properties and air temperatures for the nine slabs are summarized in Table 2.2. The table does not include the unit weight for the summer slab with 60% portland cement/25% slag/15% fly ash due to a defective scale. Table 2.2 also includes an unreasonably high unit weight for the spring slab with 100% portland cement, which is likely due to an erroneous recording. In general (and as expected), the highest concrete temperatures (81 – 90 °F) were observed in the summer slabs, with the lowest temperatures (54 – 66 °F) observed in the fall slabs. For two slabs cast in the fall, the 35% slag/65% PC and the 15% fly ash/25% slag/60% PC slabs, overnight temperatures were below freezing; insulating blankets were used for the first seven days of curing to protect these specimens from freezing. Slabs cast in the spring had moderate concrete temperatures (72 – 83 °F).

Table 2.2: Plastic Concrete Properties

Season	Concrete	Casting Date	Slump (in.)	Air Temp (°F)	Concrete Temp (°F)	Unit Wt. (lb/ft^3)	Air (%)	*w/cm* ratio⁺
Summer	100% Portland Cement (PC)	7/28/2011	3.75	92	90	140.3	7.9	0.43
	35% Slag, 65% PC	8/16/2011	3.00	79	81	143.0	5.8	0.41
	15% Fly Ash, 25% Slag, 60% PC	8/24/2011	2.50	90	86	*	5.4	0.42
Fall	100% Portland Cement (PC)	10/19/2011	1.25	43	66	141.0	7.4	0.42
	35% Slag, 65% PC	11/3/2011	1.25	40	64	144.0	5.0	0.42
	15% Fly Ash, 25% Slag, 60% PC	11/9/2011	4	44	54	139.0	7.4	0.39
Spring	100% Portland Cement (PC)	4/5/2012	0.75	55	72	147.9**	6.0	0.40
	35% Slag, 65% PC	4/19/2012	1.5	78	78	143.3	7.4	0.40
	15% Fly Ash, 25% Slag, 60% PC	4/26/2012	2.25	89	83	144.2	9.0	0.42

⁺Based on trip ticket
* Measurement not obtained
** High value – likely in error

2.4 Sample Collection and Test Procedures

2.4.1 Selecting Test Specimens for Testing

A total of 60 lab-cured cylinders and 60 field-cured cylinders were cast for each slab; 54 for testing and 6 extra cylinders in case a cylinder was damaged or unsuitable for testing. When selecting cylinders for testing, one cylinder filled at the beginning, middle, and end of the cylinder-making process was chosen for each test. Field-cured cylinders remained in the field until approximately one week prior to testing, at which time they were brought to the laboratory and maintained at 70 to 74 °F until the time of test. Lab-cured cylinders were brought to the laboratory approximately 24 hours after casting and were cured in lime-saturated water in accordance with ASTM C31 until they were prepared for testing.

The slabs were cored approximately one week prior to the testing date using a 4.25-in. diameter core bit, following the procedures outlined in KT-49. This bit produced a core with a nominal diameter of 4 in. Cores were taken perpendicular to the slab surface. After coring, the water from drilling was wiped off and the surface allowed to dry. The cores were labeled with slab and location information and placed in sealed plastic bags to limit additional moisture loss. The cores were taken to the laboratory and stored at 70 to 74 °F until testing. The coring locations were chosen so that, for each test, concrete from the beginning, middle, and end of the placement was sampled.

2.4.2 Test Procedures

2.4.2.1 Compressive Strength Test

The specimens were tested in accordance with ASTM C39. Three lab-cured cylinders, three field-cured cylinders, and three cores were tested on each test date. On the day of testing, the bottom ends were cut level using a masonry saw, but otherwise the full length was retained to provide as representative a sample as possible for evaluation of the concrete through the depth of the slab. The cores and cylinders were then capped using sulfur capping compound at least two hours prior to testing (The capping compound used in this study was rated to 9,000 psi at 2 hours). Because the cores were longer than 8 in., it was necessary to adjust the strength of the cores to correct for the fact that the length-to-diameter ratio was not equal to 2. The final compressive strength was adjusted using the following equations (KDOT 2007):

For $L/D < 2$;

$$\sigma = \sigma_u \left[\frac{100}{95 + 0.2\left(\frac{D}{L}\right) + 19.5\left(\frac{D}{L}\right)^2} \right]$$

For $L/D > 2$;

$$\sigma = \sigma_u \left[\frac{100}{110 - 5\left(\frac{L}{D}\right)} \right]$$

where:

D = core diameter, in.
L = core length, in.
σ_u = uncorrected compressive strength, psi.
σ = corrected compressive strength, psi
Strengths reported for cores are corrected compressive strengths.

2.4.2.2 Boil Test

The boil test, which measures the volume of permeable pore or void space in a concrete mixture, was performed in accordance with KDOT Test Method KT-73. Three lab-cured cylinders, three field-cured cylinders, and three cores were tested at each test date.

2.4.2.3 RCP Test

The Rapid Chloride Permeability test (RCP test) was performed at the KDOT Materials and Research Center in accordance with ASTM C1202. The RCP test measures the current passed through a 2-in. thick sample of concrete taken from a cylinder or core, and is a measure of ionic conductivity within concrete. One side of the test specimen is exposed to a sodium chloride solution while the other side is exposed to a sodium hydroxide solution. A greater charge passing through the specimen suggests a greater ionic permeability (ASTM C1202). Three lab-cured cylinders, three field-cured cylinders, and three cores were tested at each test date.

CHAPTER 3: SUMMARY OF RESULTS

This chapter presents a summary of findings from this study, with a focus on establishing relationships between the concrete properties evaluated in this study (strength, permeability, and porosity) and the age and sampling method of the concrete. Individual results are presented in Appendix A, and a more detailed analysis of results is presented by O'Reilly et al. (2016). Throughout this report, slabs containing 100% portland cement will be identified as "PC" in figures and tables; mixtures with 65% portland cement/35% slag and 60% portland cement/25% slag/15% fly ash are identified as "PC/S" and "PC/S/FA", respectively.

3.1 Compressive Strength

3.1.1 Comparisons between Cylinders and Cores

Figure 3.1 gives the average 28-day compressive strength for lab-cured cylinders, field-cured cylinders, and cores for each of the nine slabs. Error bars indicate the range in results. All specimens exhibited an average compressive strengths (as measured by lab-cured cylinders) over 4,000 psi. For seven of the nine slabs, the lab-cured cylinders exhibited the greatest compressive strength; for the summer slab with 60% portland cement/25% slag/15% fly ash (PC/S/FA) and the fall slab with 65% portland cement/35% slag (PC/S), the cores exhibited slightly greater compressive strengths than the lab-cured cylinders. The field-cured cylinders exhibited the lowest compressive strengths in seven out of nine cases; the difference was most dramatic in the summer [likely due to moisture loss at the high temperatures experienced by the field-cured cylinders and the negative effect of high temperatures at early ages on long-term strength (Mindess et al. 2003)].

For all mixtures, the greatest 28-day compressive strengths were observed in the spring, where the concrete temperatures during placement were moderate. The 60% portland cement/25% slag/15% fly ash (PC/S/FA) mixture exhibited significantly lower temperatures in the fall than in the spring or summer; it is likely that the lower ambient temperatures coupled with the lower heat of hydration of mixtures containing SCMs, PC/S and PC/S/FA, relative to those with only portland cement resulted in delayed hydration and lower strength gain at early ages.

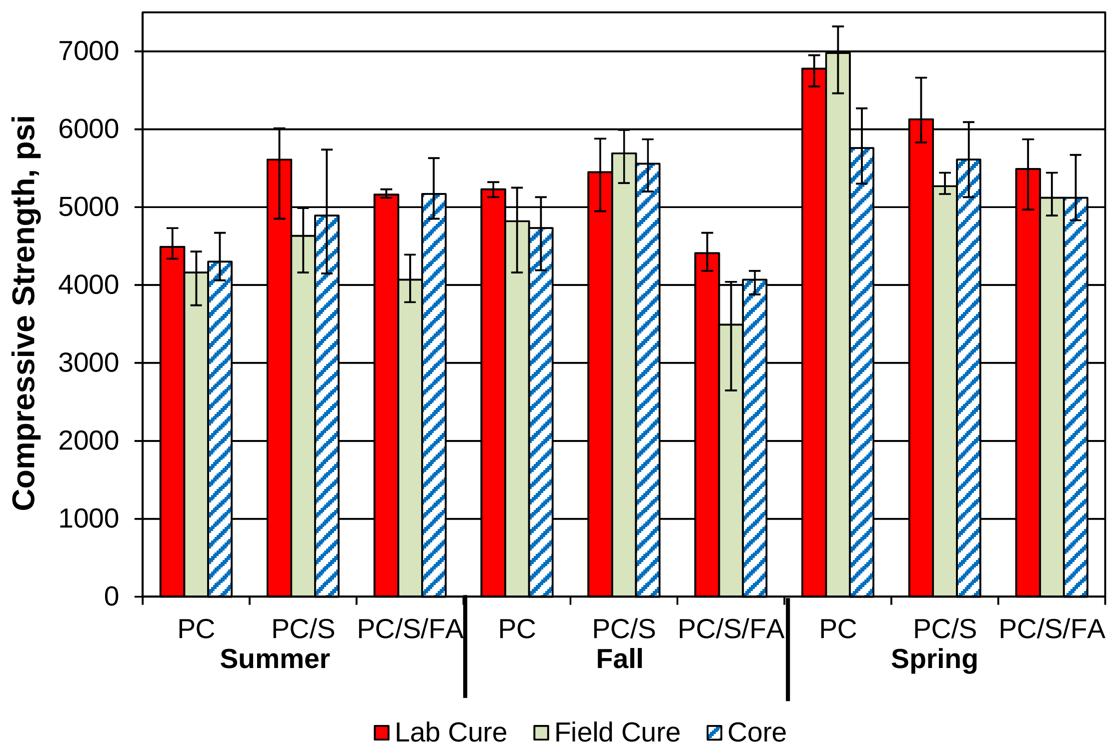

Figure 3.1: Average 28-day compressive strength

Figure 3.2 presents the ratio of core strength to lab-cured cylinder strength for all slabs at all ages. A ratio greater than 1 indicates the average core strength was greater than the average lab-cured cylinder strength at that age. As shown in the figure, cores exhibited lower strength than lab-cured cylinders in 45 out of 54 comparisons. No clear trends with respect to age or mixture type were observed. On average, the ratio of core to lab-cured cylinder strength was 0.94, with a range of 0.79 to 1.26. For all comparisons at all ages, the average ratios were 0.91, 0.97, and 0.94, respectively, for slabs cast in the summer, fall, and spring.

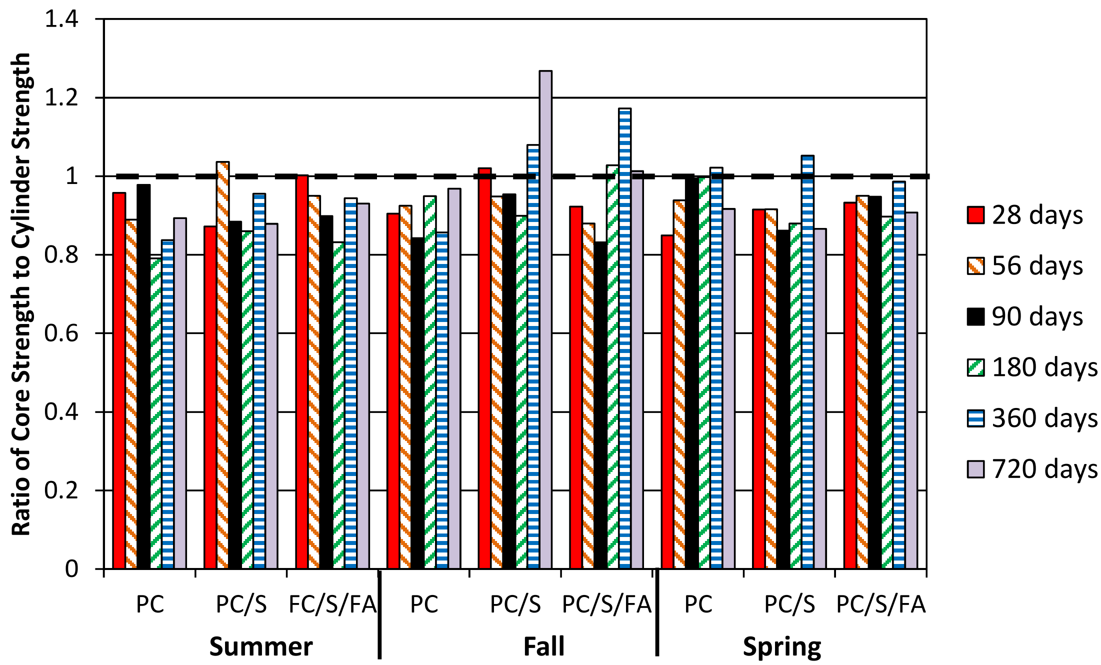

Figure 3.2: Ratio of core strength to lab-cured cylinder strength

Figure 3.3 presents the ratio of core strength to field-cured cylinder strength for all slabs at all ages. Unlike the comparison with the lab-cured cylinders, cores exhibited greater strength than field-cured cylinders in 41 out of 54 comparisons. No clear trends with respect to age or mixture type were observed. On average, the ratio of core to field-cured cylinder strength was 1.05, with a range of 0.83 to 1.27. For all comparisons at all ages, the average ratios were 1.09, 1.03, and 1.03 respectively, for slabs cast in the summer, fall, and spring.

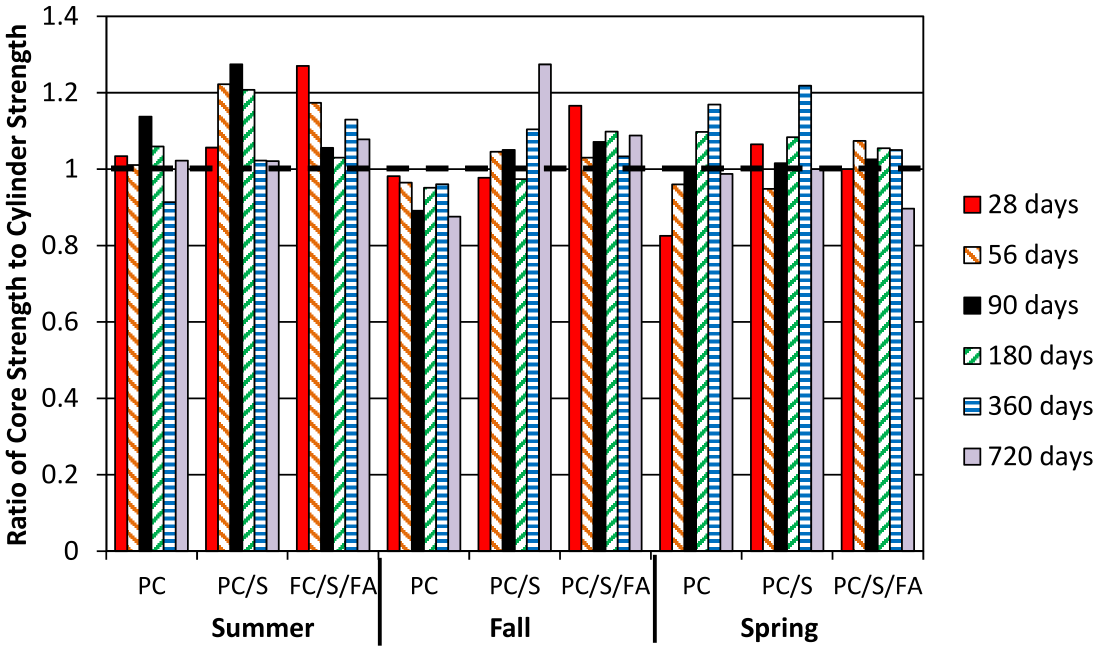

Figure 3.3: Ratio of core strength to field-cured cylinder strength

Figure 3.4 presents the ratio of field-cured strength to lab-cured cylinder strength for all slabs at all ages. Field-cured cylinders exhibited a greater strength than lab-cured cylinders in just 5 out of 54 cases. This trend was especially apparent in the summer slabs, where drying due to the higher ambient temperatures likely harmed the strength of the field-cured cylinders. On average, the ratio of field-cured to lab-cured cylinder strength was 0.89, with a range of 0.69 to 1.13. For the summer placements, the average ratio of field-cured to lab-cured cylinder strength was 0.83, significantly below values of 0.94 and 0.91 for the fall and spring slabs, respectively. No field-cured cylinder cast in the summer exhibited a strength greater than the corresponding lab-cured cylinder.

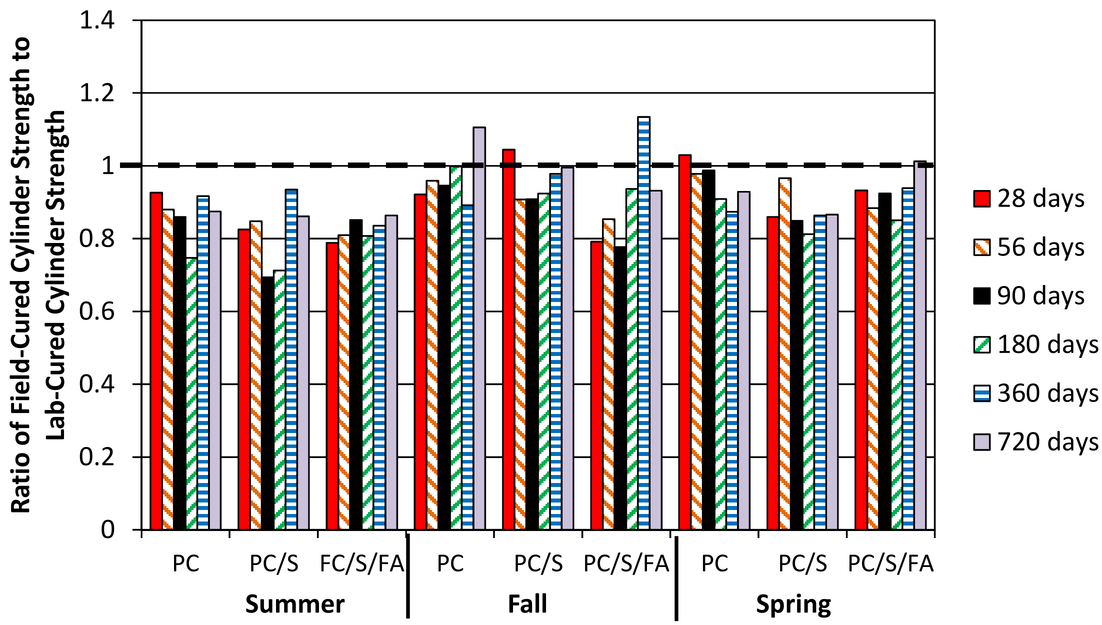

Figure 3.4: Ratio of field-cured cylinder strength to lab-cured cylinder strength

3.1.2 Strength Variation with Age

Figures 3.5a, 3.5b, and 3.5c show the compressive strength for *lab-cured cylinders* normalized to the 28-day compressive strength for, respectively, the 100% portland cement (PC), 65% portland cement/35% slag (PC/S), and 60% portland cement/25% slag/15% fly ash (PC/S/FA) mixtures. Although there were significant variations in individual results, compressive strengths at later ages were greater than the 28-day strengths, with the strength increasing, on average, to 120% of the 28-day strength by 360 days. After 360 days, the strength of the 100% portland cement and 65% portland cement/35% slag mixtures leveled off (with cylinders from five out six slabs exhibiting some decrease in strength at 720 days), whereas the 60% portland cement/25% slag/15% fly ash mixtures saw further increases in strength through 720 days in two out of three cases (a drop occurred for the summer slab), reaching an average strength about 30% above the 28-day average. The lack of seasonal dependence shown in the figures is expected, as the lab-cured cylinders were stored in a climate-controlled environment.

The spring mixture containing 100% portland cement exhibited significantly less strength gain after 28 days than other mixtures and the largest drop in strength (15 %) between 360 and 720 days. This was the only slab of the nine to exhibit such an extreme drop. Some cylinders from this slab were poorly consolidated due to the low slump of the concrete; this may have resulted in lower apparent strengths if the cylinders tested at later ages had voids (although this was not recorded), causing subsequent comparisons to the 28-day strength to be artificially low. Variations in strength, particularly spikes or drops in strength at a specific age, were observed to a lesser extent on other cylinders and cores, as will be seen in subsequent figures. These variations may be due to natural variation in the concrete or may be a result of having multiple personnel molding cylinders, thus introducing variation in the degree of consolidation of the cylinders.

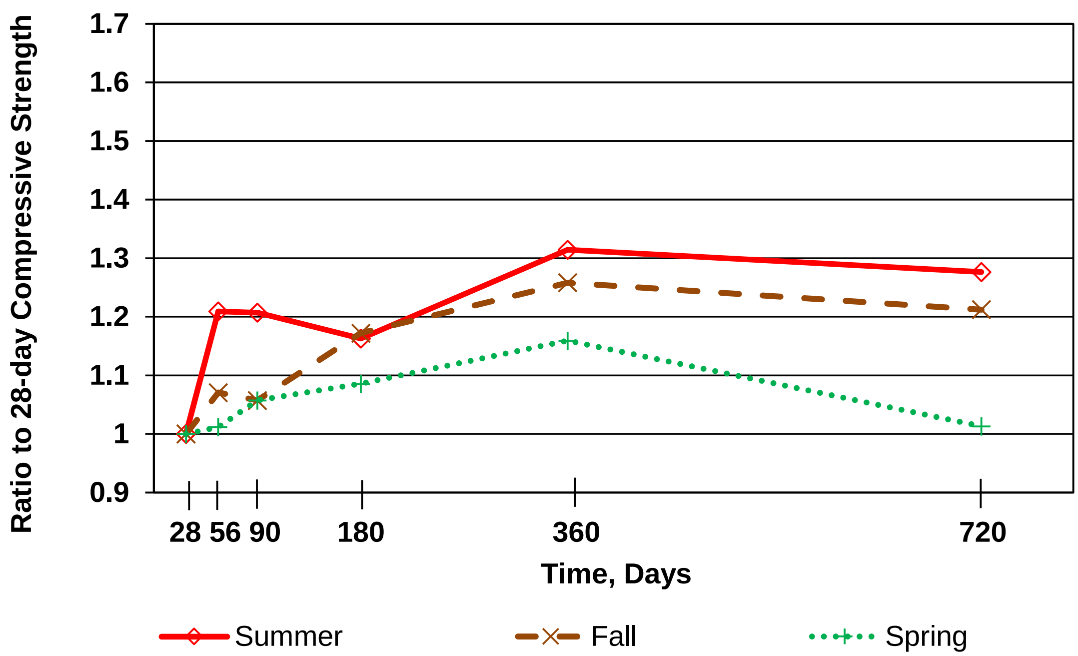

Figure 3.5a: Compressive strength normalized to 28-day values for lab-cured cylinders from 100% portland cement (PC) mixtures

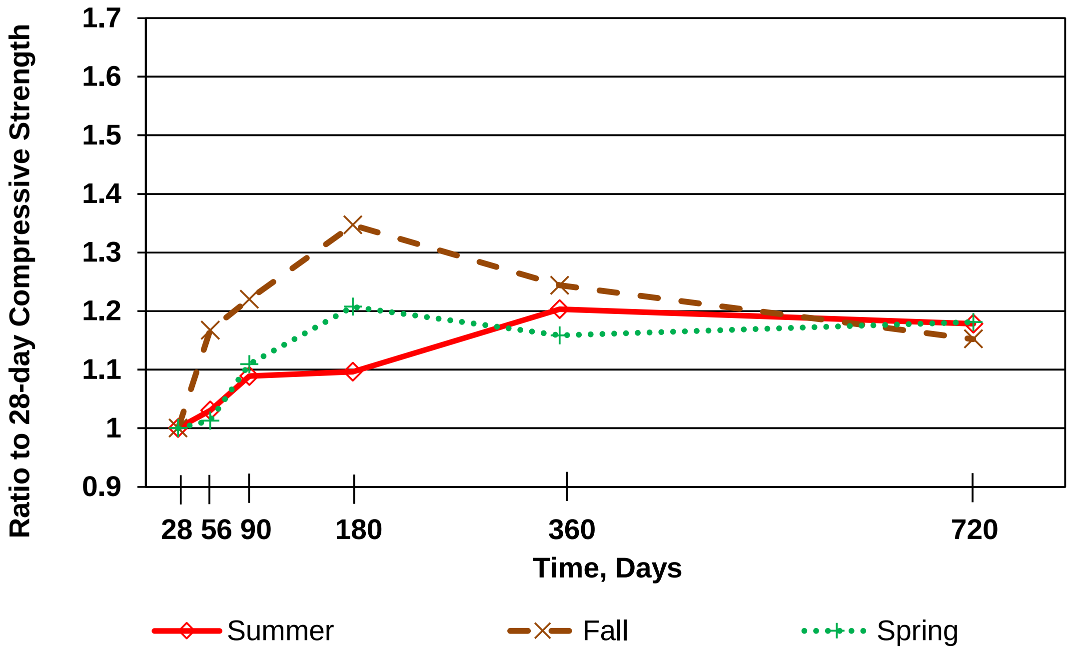

Figure 3.5b: Compressive strength normalized to 28-day values for lab-cured cylinders from 65% portland cement/35% slag (PC/S) mixtures

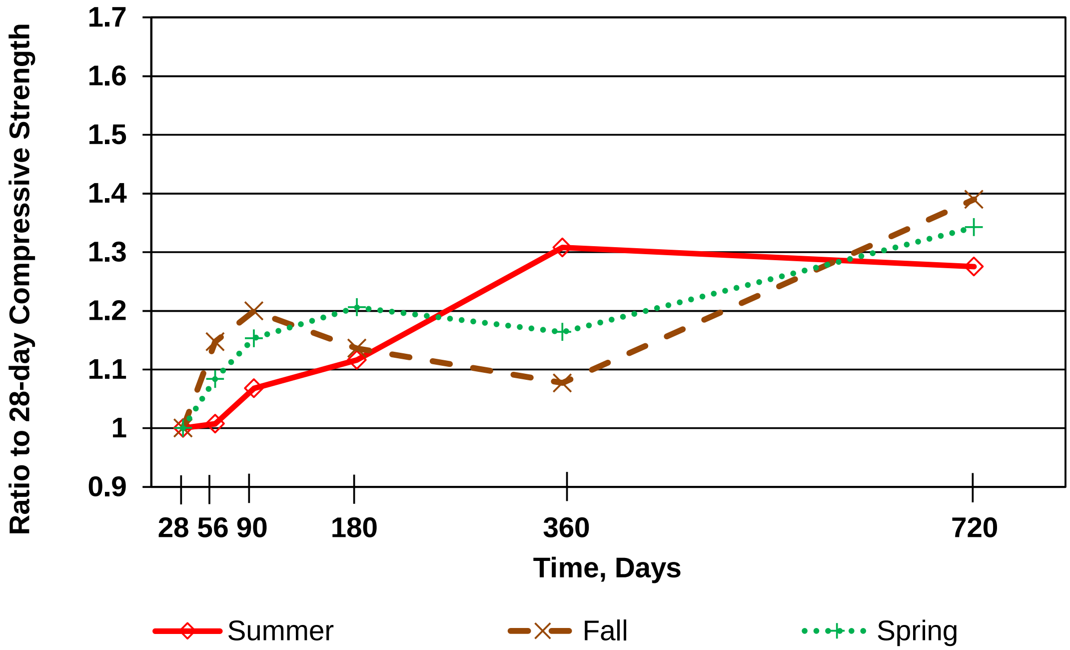

Figure 3.5c: Compressive strength normalized to 28-day values for lab-cured cylinders from 60% portland cement/25% slag/15% fly ash (PC/S/FA) mixtures

Figures 3.6a, 3.6b, and 3.6c show the compressive strength for *field-cured cylinders* normalized to the 28-day compressive strength (from field-cured cylinders) for, respectively, the 100% portland cement (PC), 65% portland cement/35% slag (PC/S), and 60% portland cement/25% slag/15% fly ash (PC/F/FA) mixtures. There was a wide degree of variation in individual results, as was observed for lab-cured cylinders. Compressive strength increased to an average of 125% of the 28-day strength by 360 days, with no apparent dependence on season. As observed for the lab-cured cylinders, the strength of the 100% portland cement and 65% portland cement/35% slag mixtures generally leveled off after 360 days. The 60% portland cement/25% slag/15% fly mixtures, however, saw significant increases in strength through 720 days, particularly for the slabs cast in the fall. The 60% portland cement/25% slag/15% fly ash slab cast in the fall experienced the lowest early age temperatures and had the lowest 28-day strength; the data demonstrate that long-term strength was not harmed by these exposure conditions. As was observed for the lab-cured cylinders, the spring 100% portland cement mixture exhibited significantly lower strength gain than any other mixture-compressive strengths at later ages with strengths that were, except at 90 days, *lower* than the 28-day strength. Given that this was the only series of field-cured cylinders to exhibit this behavior, it is likely that the consistently low longer-term strength is due to the poor consolidation of some cylinders (as discussed for the lab-cured cylinders) and may not be representative of the true behavior of the concrete.

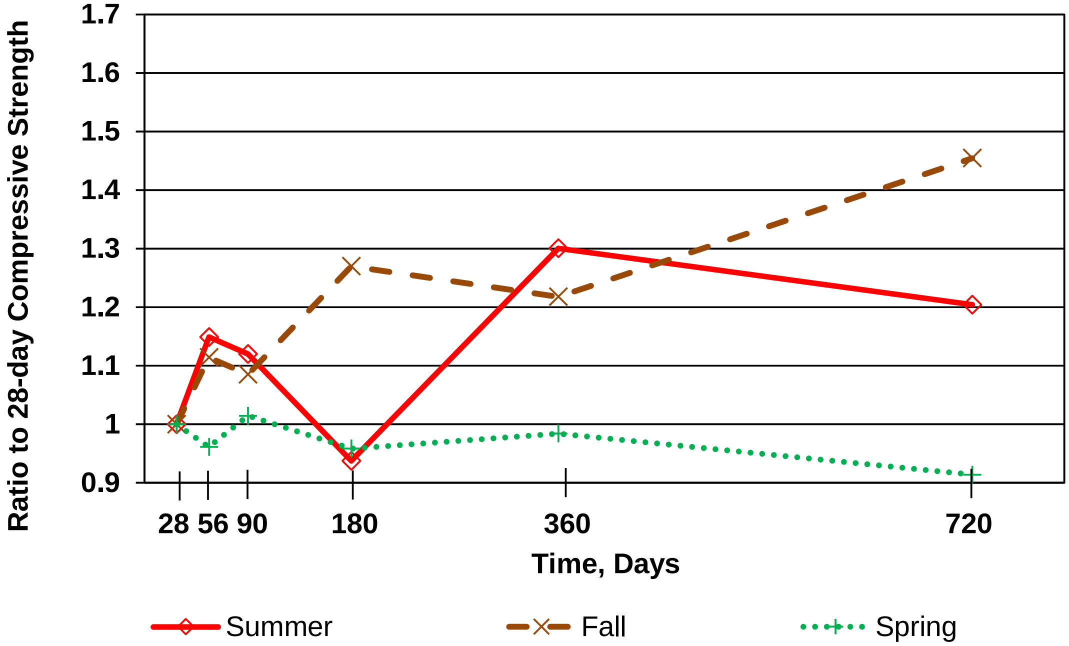

Figure 3.6a: Compressive strength normalized to 28-day values for field-cured cylinders from 100% portland cement (PC) mixtures

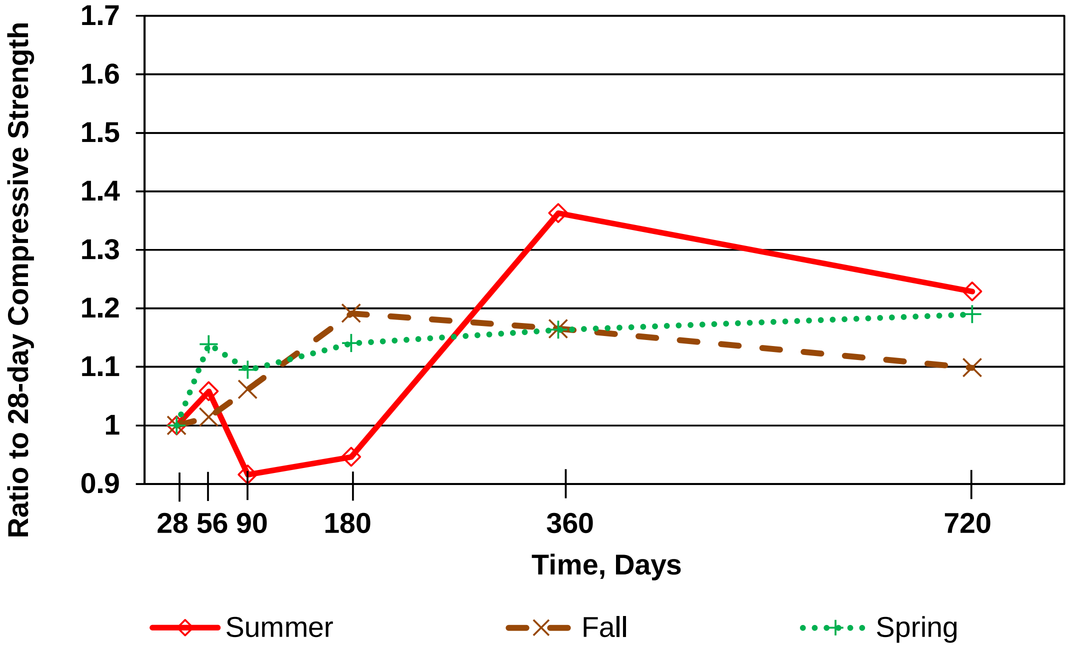

Figure 3.6b: Compressive strength normalized to 28-day values for field-cured cylinders from 65% portland cement/35% slag (PC/S) mixtures

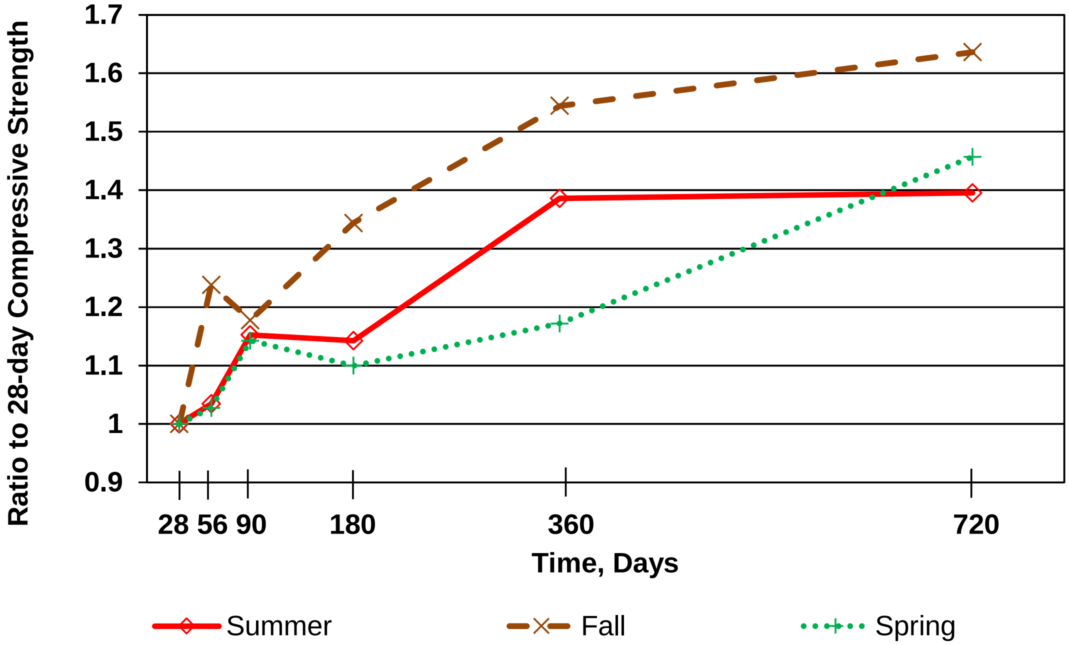

Figure 3.6c: Compressive strength normalized to 28-day values for field-cured cylinders from 60% portland cement/25% slag/15% fly ash (PC/S/FA) mixtures

Figures 3.7a, 3.7b, and 3.7c show the compressive strength for *cores* normalized to the 28-day compressive strength (from cores) for 100% portland cement (PC), 65% portland cement/35% slag (PC/S), and 60% portland cement/25% slag/15% fly ash (PC/S/FA) mixtures, respectively. A later ages, compressive strength was generally greater than the 28-day strength, with an average of 120 to 130% of the 28-day strength at 360 days. The strength of the 100% portland cement and 65% portland cement/35% slag mixtures, on average, leveled off after 360 days, whereas the 60% portland cement/25% slag/15% fly ash mixtures exhibited significant increases in strength through 720 days for the slabs cast in fall and spring. The cores from the spring slab with 100% portland cement exhibited behavior similar to that of other slabs, in contrast to the low strengths observed for the cylinders, suggesting the low cylinder strengths were indeed due to poor consolidation of some specimens and is not indicative of the true behavior of the concrete. Like both sets of cylinders for this slab, however, the cores did exhibit a drop in strength between 360 and 720 days. Overall, a drop in strength between 360 and 720 days occurred in about half (14 of the 27) of the comparisons shown in Figures 3.5 through 3.7. This observation, supports the expectation that increases in concrete strength will be low a later ages and suggests that the observed differences in strength after 360 days may be due to the inherent variability of concrete.

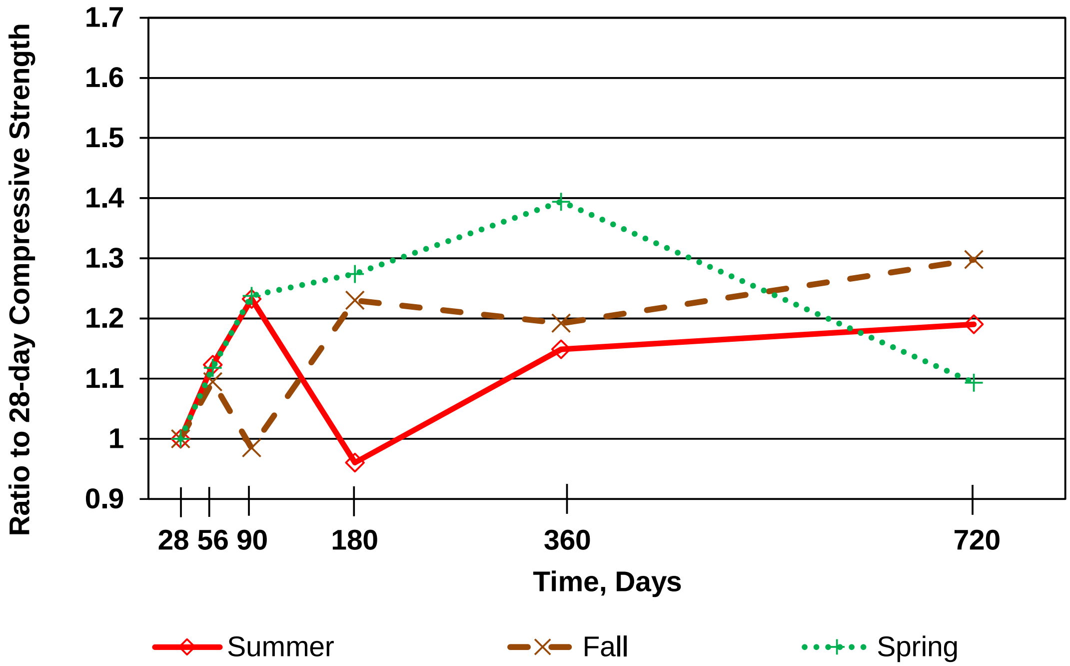

Figure 3.7a: Compressive strength normalized to 28-day values for cores from 100% portland cement (PC) mixtures

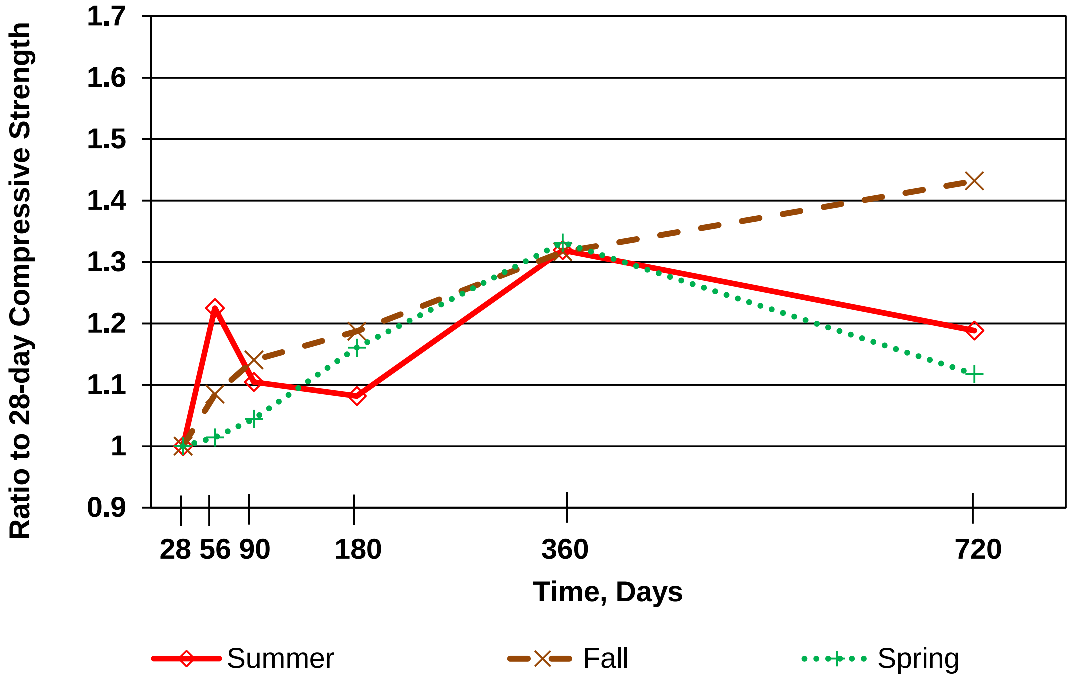

Figure 3.7b: Compressive strength normalized to 28-day values for cores from 65% portland cement/35% slag (PC/S) mixtures

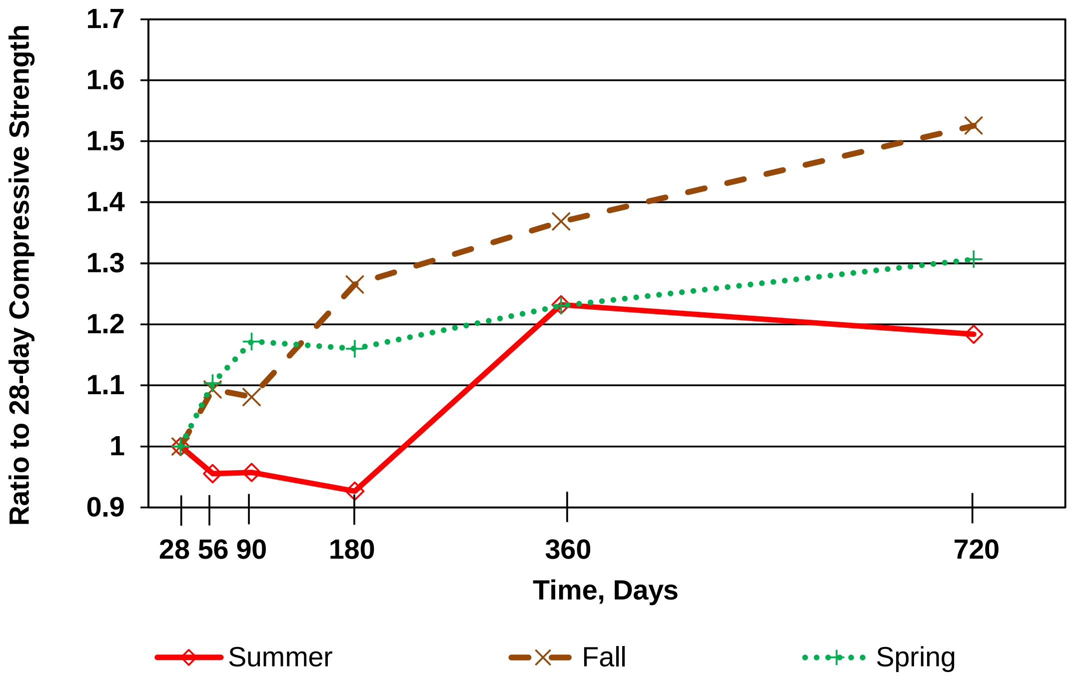

Figure 3.7c: Compressive strength normalized to 28-day values for cores from 60% portland cement/25% slag/15% fly ash (PC/S/FA) mixtures

3.1.3 Representative Equations

Table 3.1 summarizes the ratios of field-cured cylinder and core strengths to lab-cured cylinder strength. The findings for cores suggest that the current guidelines for acceptance of core strength (average of $0.85 f_c'$ with no single core below 0.75 f'_c) are adequate. Field-cured cylinders generally exhibited lower strengths than cores; as discussed in Section 3.1.1, this is impacted the most by the results for the slab cast in the summer because of moisture loss at high temperatures at early ages and the negative effect of high temperatures at early ages on long-term strength.

Table 3.1: Ratio of average strength of field-cured cylinders and cores to average strength of lab-cured cylinders – all specimens at all ages

Specimen	Average	Summer	Fall	Spring	Range
Field-Cured Cylinders	0.89	0.83	0.94	0.91	0.69 to 1.13
Cores	0.94	0.91	0.97	0.94	0.79 to 1.26

The ratio of the strength of concrete at later ages to the 28-day strength, presented in Figures 3.5 through 3.7, may be represented as follows:

For mixtures containing only portland cement, slag cement, or both,

$$\sigma_t = \sigma_{28}\left(0.08\ \ln(t) + 0.733\right)\ \leq 1.20\sigma_{28} \qquad (1a)$$

t = test age of cylinder, days ($28 \leq t \leq 720$)

σ_{28} = 28-cylinder (or core) compressive strength, and

σ_t = cylinder (or core) compressive strength

For mixtures containing a minimum of 15% Class C fly ash,

$$\sigma_t = \sigma_{28}\left(\alpha \ln(t) + \beta\right) \qquad (1b)$$

t = test age of cylinder, days ($28 \leq t \leq 720$)

α, β = as defined in Table 3.2

Table 3.2: α and β values for use in Eqs. (1b) and (2b)

	Mixtures Containing 15% Class C Fly Ash		**Other Cases**	
Specimen Type	**α**	**β**	**α**	**β**
Lab-Cured Cylinder	0.08	0.733	0.08	0.733
Field-Cured Cylinder	0.145	0.517	0.08	0.733
Core	0.10	0.667	0.08	0.733

Equations (1a) and (1b) were determined using a least-squares regression analysis to determine the coefficients, with the goal of minimizing the difference between the ratio (strength at time t to 28-day strength) predicted by the equation to the ratios found from testing. These comparisons are shown in Figures 3.8a, 3.8b, and 3.8c for mixtures containing 100% portland cement, 65% portland cement/35% slag cement, and 60% portland cement/25% slag cement/15% fly ash, respectively. Equation (1a) rises to $1.20\sigma_{28}$ at t = 360 days and is constant thereafter. Equation (1b) continues to rise to t = 720 days.

The mean, standard deviation, maximum, and minimum of comparisons of the test results to the values calculated using Eq. (1a) and (1b) are presented in Table 3.3. At ages between 28 and 720 days, the mean varies between 0.986 and 1.029, with maximum and minimum values of 1.172 and 0.781, respectively. The low overall coefficient of variation, 0.083, indicates that the test data are well represented by Eq. (1a) and (1b). The wide degree of variation observed in the figures, however, indicates that the behavior of concrete at a particular jobsite may vary from that predicted by Eq. (1a) and (1b).

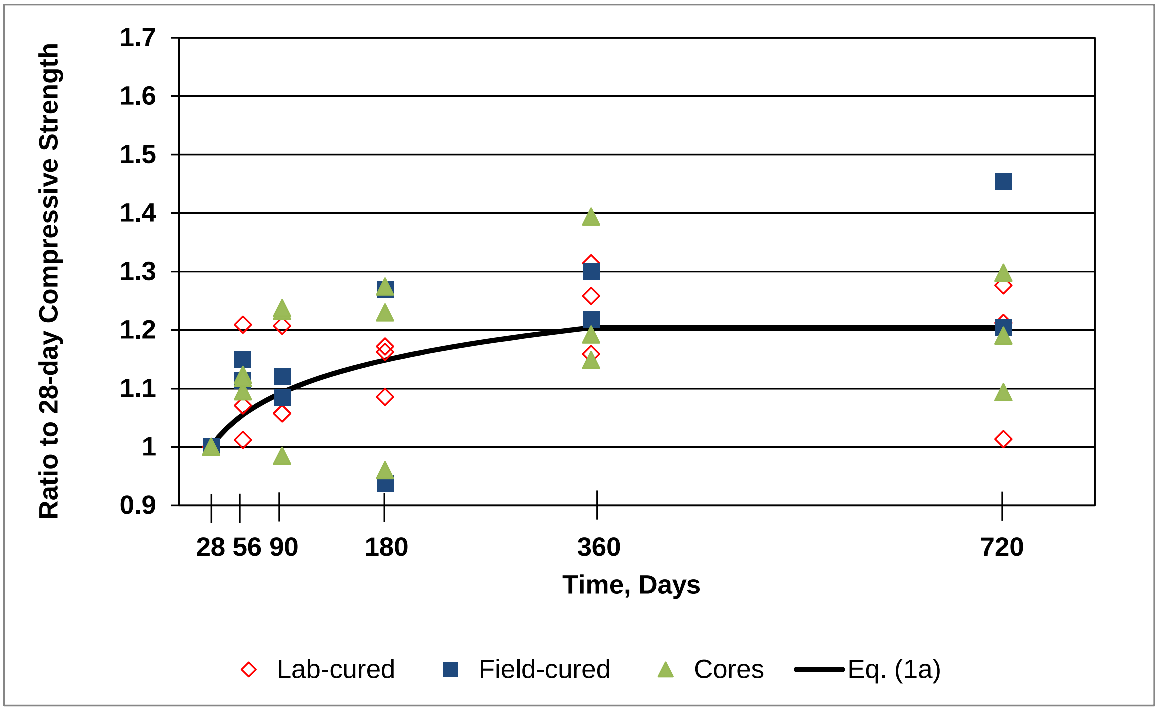

Figure 3.8a: Compressive strength normalized to 28-day values and predictive equation for 100% portland cement (PC) mixtures

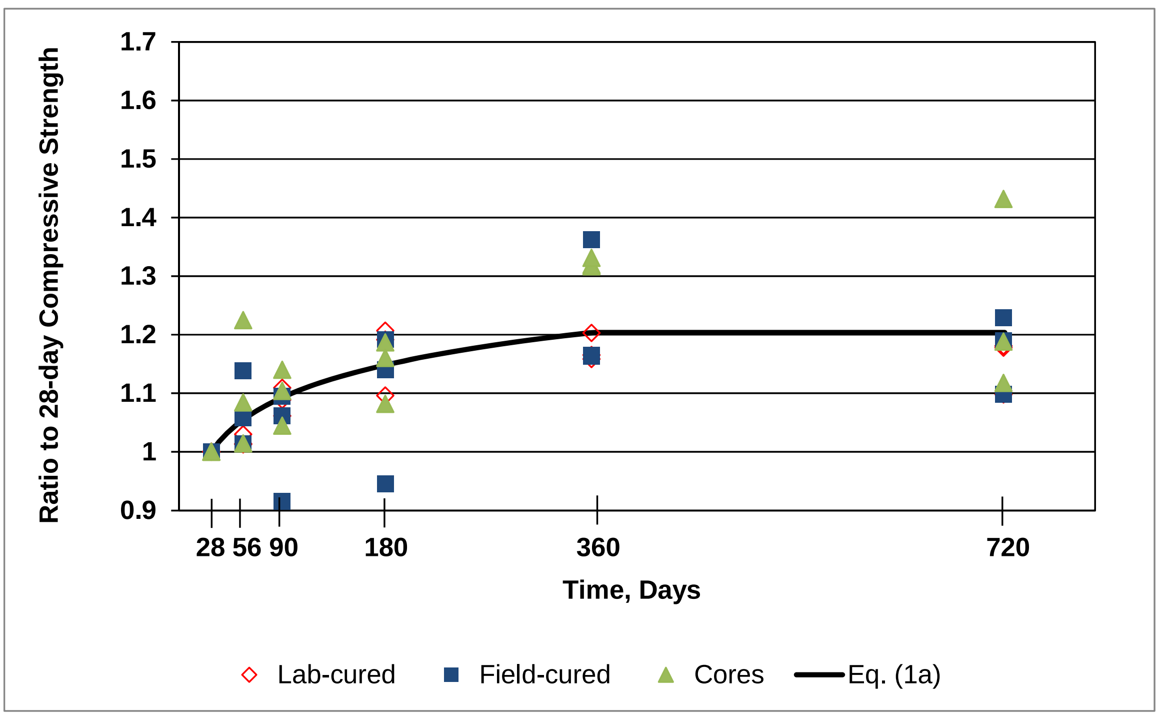

Figure 3.8b: Compressive strength normalized to 28-day values and predictive equation for 65% portland cement/35% slag (PC/S) mixtures

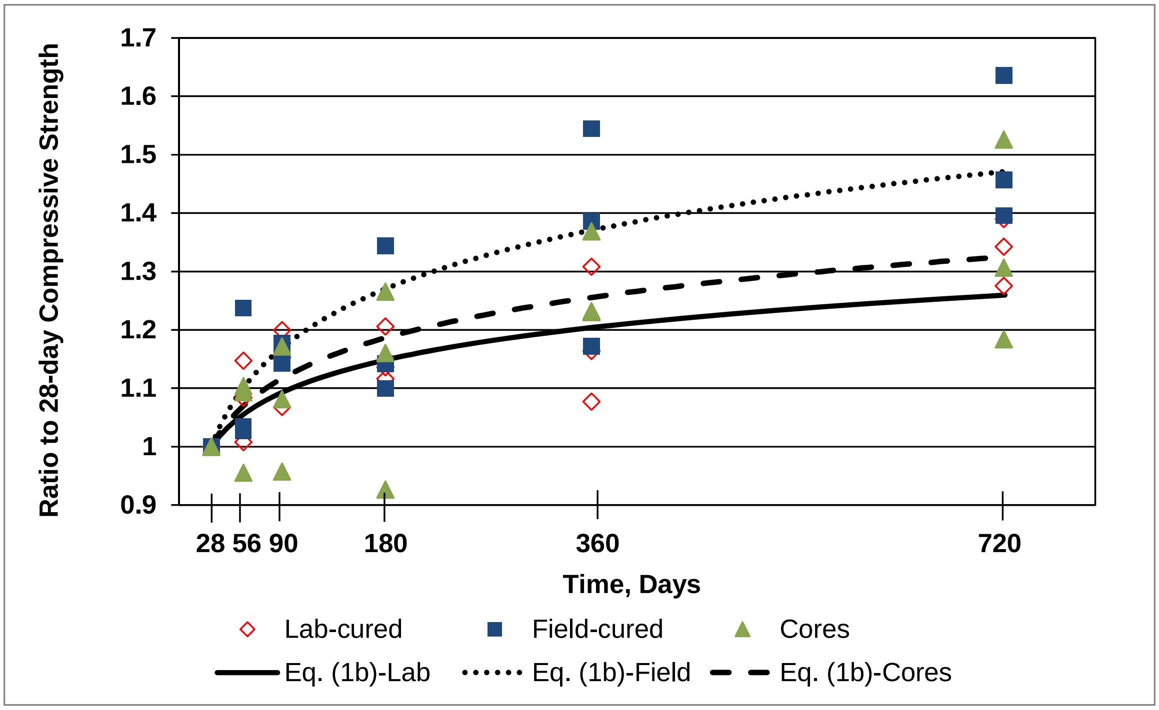

Figure 3.8c: Compressive strength normalized to 28-day values and predictive equation for 60% portland cement/25% slag cement/15% fly ash (PC/S/FA) mixtures

Table 3.3: Statistical parameters for comparisons of test results to values calculated using Eq. (1a) and (1b)

Age	Mean	Standard Deviation	COV	Max	Min
28	1	-	-	-	-
56	1.029	0.070	0.068	1.161	0.894
90	1.007	0.076	0.075	1.132	0.838
180	0.986	0.101	0.102	1.172	0.781
360	1.027	0.077	0.075	1.158	0.855
720	0.990	0.087	0.088	1.154	0.868
All	**1.008**	**0.083**	**0.083**	**1.172**	**0.781**

Because most strength requirements are expressed in terms of a minimum 28-day strength, it is desirable to express Eq. (1a) and (1b) in terms of the estimated 28-day strength based on a cylinder tested at a later age.

For mixtures containing portland only cement, slag cement, or both:

$$\sigma_{28} = \frac{\sigma_t}{0.08\ \ln(t) + 0.733} \tag{2a}$$

t = test age of cylinder, days ($28 \leq t \leq 360$)

σ_{28} = predicted 28-cylinder (or core) compressive strength, and

σ_t = cylinder (or core) compressive strength at time t.

For $360 \leq t \leq 720$, use $t = 360$ in Eq. (2a).

For mixtures containing a minimum of 15% Class C fly ash,

$$\sigma_{28} = \frac{\sigma_t}{\alpha \ln(t) + \beta} \tag{2b}$$

t = test age of cylinder, days ($28 \leq t \leq 720$)

α, β = as defined in Table 3.2

It is noted that Eq. (2b) may be used with all mixtures, provided a 360-day limit is applied to t for mixtures not containing at least 15% Class C fly ash.

3.2 RAPID CHLORIDE PERMEABILITY (RCP) TEST RESULTS

3.2.1 Comparisons between Cylinders and Cores

Figure 3.9 shows the average 56-day charge passed for lab-cured cylinders, field-cured cylinders, and cores for each of the nine slabs. Error bars indicate the range in results. All lab-cured cylinders exhibited an average charge passed less than the 3,500 coulomb limit specified by KDOT. Field-cured cylinders exhibited a greater charge passed than lab-cured cylinders for all nine slabs, in some cases over 1,000 coulombs greater than the average value for the lab-cured cylinders. This difference was most pronounced in the summer, likely due to the high summer temperatures causing excessive moisture loss in the cylinders. Cores exhibited an average RCP result between those of the lab-cured and field-cured cylinders, with the exception of the fall slabs containing SCMs, P/S and P/S/FA, where the cores exhibited the greatest charge passed, and the spring slab containing only portland cement, PC, where cores exhibited the least charge passed. The test results for field-cured cylinders or cores exhibited greater of scatter than those for lab-cured cylinders.

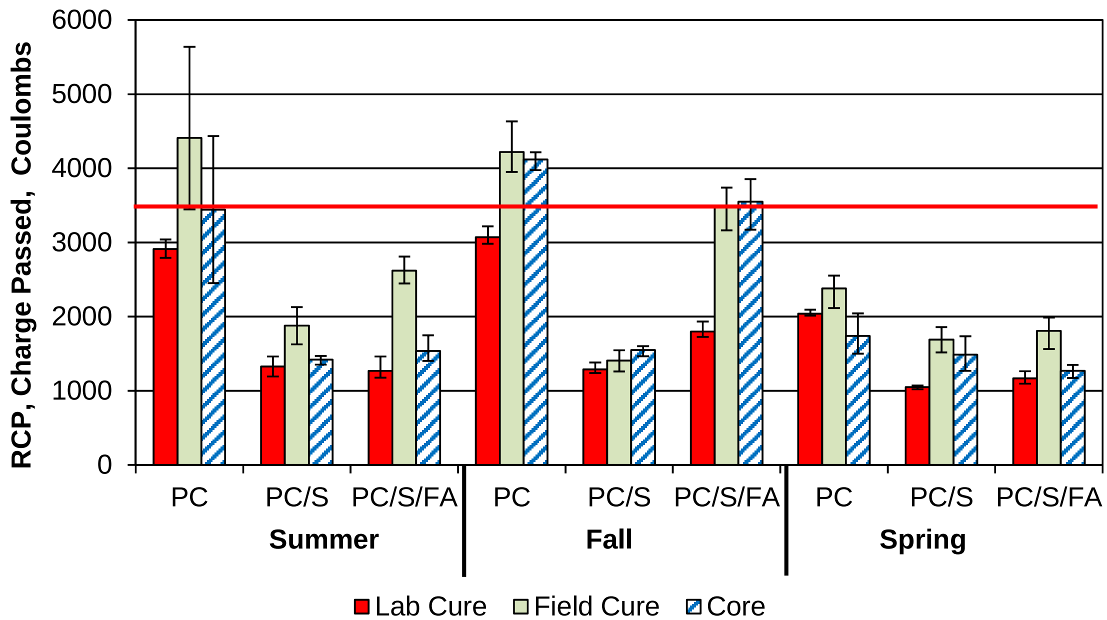

Figure 3.9: Average 56-day RCP results

In all cases, the addition of slag cement, with or without fly ash, significantly reduced the charge passed compared to specimens with only portland cement. The fall slab containing slag and fly ash, P/S/FA, exhibited the highest charge passed of any mixture containing SCMs and was the only slab containing SCMs where field-cured cylinders or cores exceeded 3,500 coulombs. This slab was exposed to the coldest early-age temperatures of any slab; it is likely the combination of the SCMs and the cold temperatures slowed hydration through 56 days. For all mixtures, the lowest charge passed occurred in the spring slabs, where the concrete temperatures were moderate.

Figure 3.10 presents the ratio of the charge passed for the cores to the charge passed for the matching lab-cured cylinders for all slabs at all ages. A ratio greater than 1 indicates the average charge passed for the cores was greater than the average charge passed for the lab-cured cylinders at that age. As shown in the figure, cores exhibited a greater charge passed than lab-cured cylinders in 48 out of 54 cases; in some cases, the cores exhibited over twice the charge passed by the lab-cured cylinders. No clear trends with respect to age or mixture type were observed. The difference between cores and lab-cured cylinders was greatest for slabs cast in the summer, followed by slabs cast in the fall and spring. The moderate temperatures in the spring most closely mirrored the curing conditions for the lab-cured cylinders, explaining lower difference between cores and lab-cured cylinders from the spring slabs. On average, cores exhibited 1.34 times the charge passed by lab-cured cylinders, with a range of 0.85 to 2.48. For all comparisons at all ages, the average ratios were 1.45, 1.39, and 1.19, respectively, for slabs cast in the summer, fall, and spring.

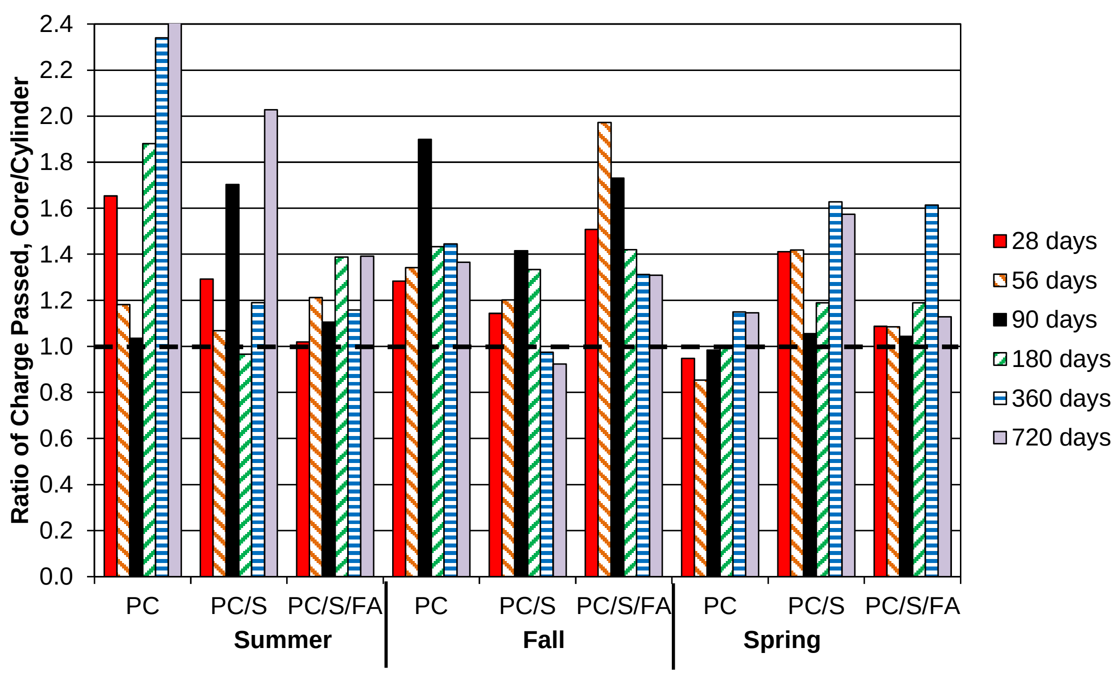

Figure 3.10: Ratio of charge passed by cores to charge passed by matching lab-cured cylinders in RCP test

Figure 3.11 presents the ratio of the charge passed for the cores to the charge passed for the matching field-cured cylinders for all slabs at all ages. As shown in the figure, the cores exhibited a lower charge passed than the field-cured cylinders in 43 out of 54 cases. No clear trends with respect to age or mixture type were observed. As was observed with lab-cured cylinders, the ratio of core strength to field-cured cylinder strength is lowest in the spring. On average, cores exhibited 0.86 times the charge passed compared to field-cured cylinders, with a range of 0.46 to 1.52. For all comparisons at all ages, the average ratios were 0.90, 0.91, and 0.79, respectively, for slabs cast in the summer, fall, and spring.

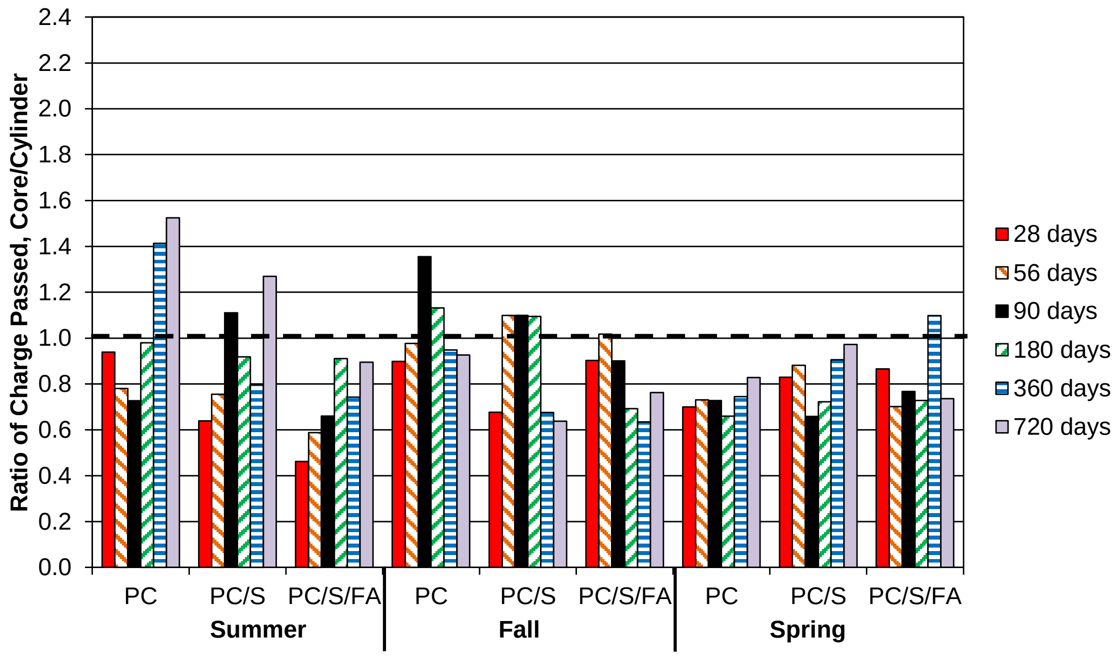

Figure 3.11: Ratio of charge passed by cores to charge passed by matching field-cured cylinders in RCP test

Figure 3.12 presents the ratio of the charge passed for the field-cured cylinders to the charge passed for the matching lab-cured cylinders for all slabs at all ages. In every case, the field-cured cylinders exhibited a greater charge passed than the lab-cured cylinders. No clear trends with respect to age or mixture type were observed. On average, field-cured cylinders exhibited 1.56 times the charge passed compared to field-cured cylinders, with a range of 1.05 to 2.21. For all comparisons at all ages, the average ratios were 1.64, 1.55, and 1.50, respectively, for slabs cast in the summer, fall, and spring.

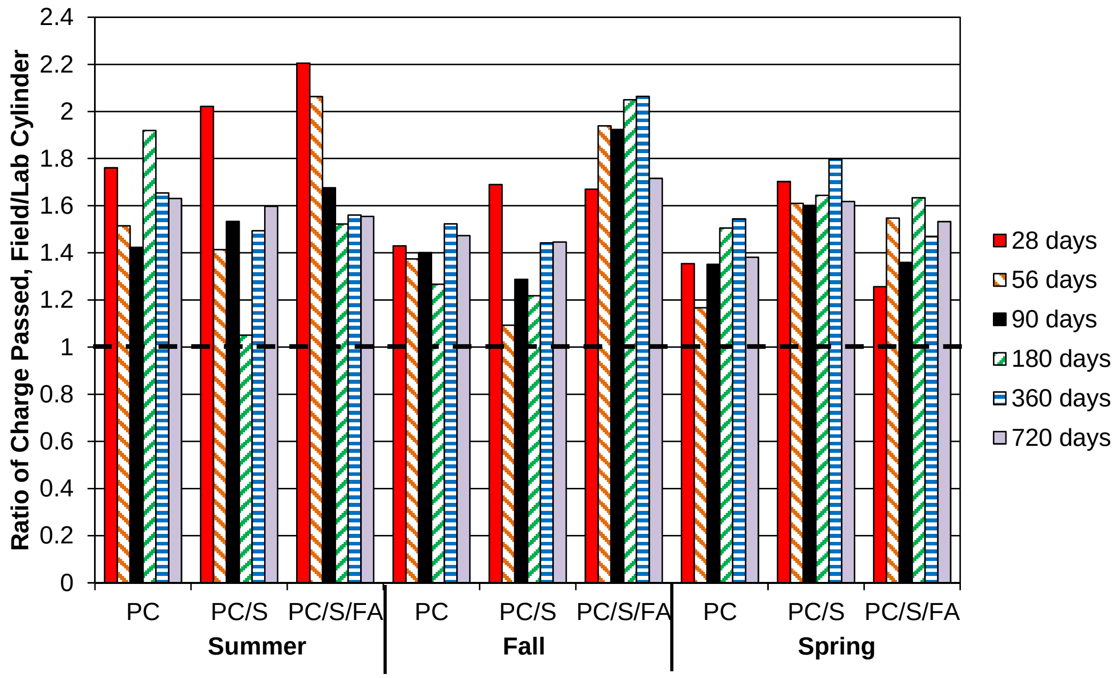

Figure 3.12: Ratio of field-cured cylinder RCP to lab-cured cylinder RCP

3.2.2 Charge Passed in RCP Test–Variation with Age

Figures 3.13a, 3.13b, and 3.13c show the charge passed for *lab-cured cylinders* normalized to the 56-day values for the 100% portland cement (PC), 65% portland cement/35% slag (PC/S), and 60% portland cement/25% slag/15% fly ash (PC/S/FA) mixtures, respectively. Although individual readings varied, the same general trends were observed across all mixtures, regardless of season–the charge passed experienced an exponential decrease over time. The values at 28 days were generally 20% to 40% greater than those at 56 days, with the rate of decrease slowing at later ages. The values of charge passed at 360 days were approximately 75% of those at 56 days. The lack of seasonal dependence is expected, as the lab-cured cylinders were stored in a climate-controlled environment. Small, isolated jumps in permeability, such as observed for cylinders from the summer slab with 60% portland cement, 25% slag, and 15% fly ash between 56 and 90 days, are likely due to statistical variation.

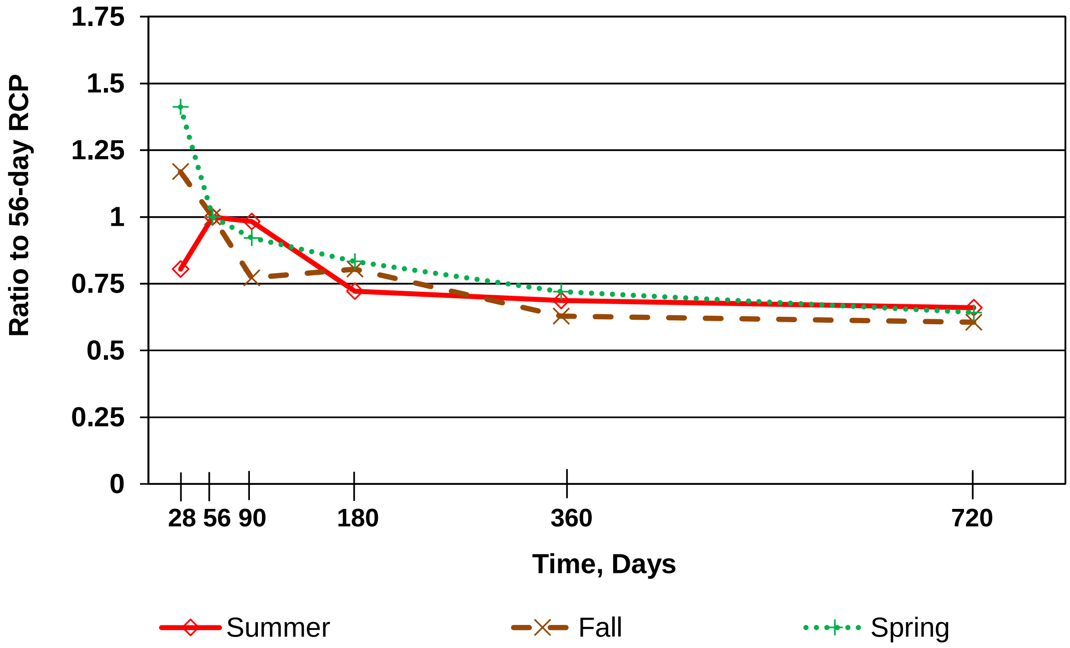

Figure 3.13a: Charge passed in RCP test normalized to values at 56 days for lab-cured cylinders from 100% portland cement (PC) mixtures

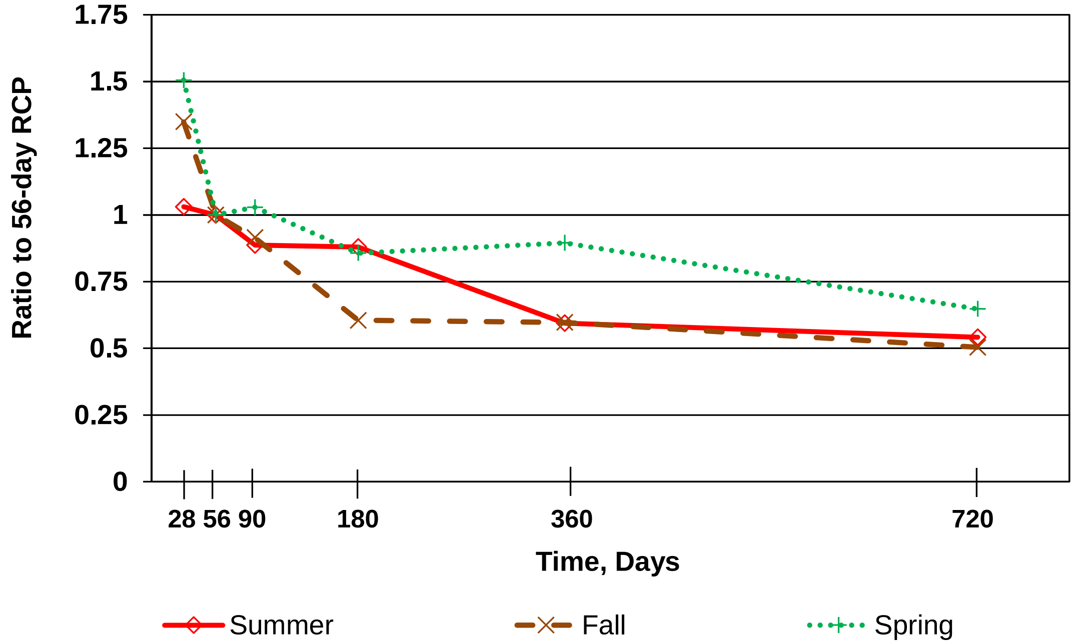

Figure 3.13b: Charge passed in RCP test normalized to values at 56 days for lab-cured cylinders from 65% portland cement/35% slag (PC/S) mixtures

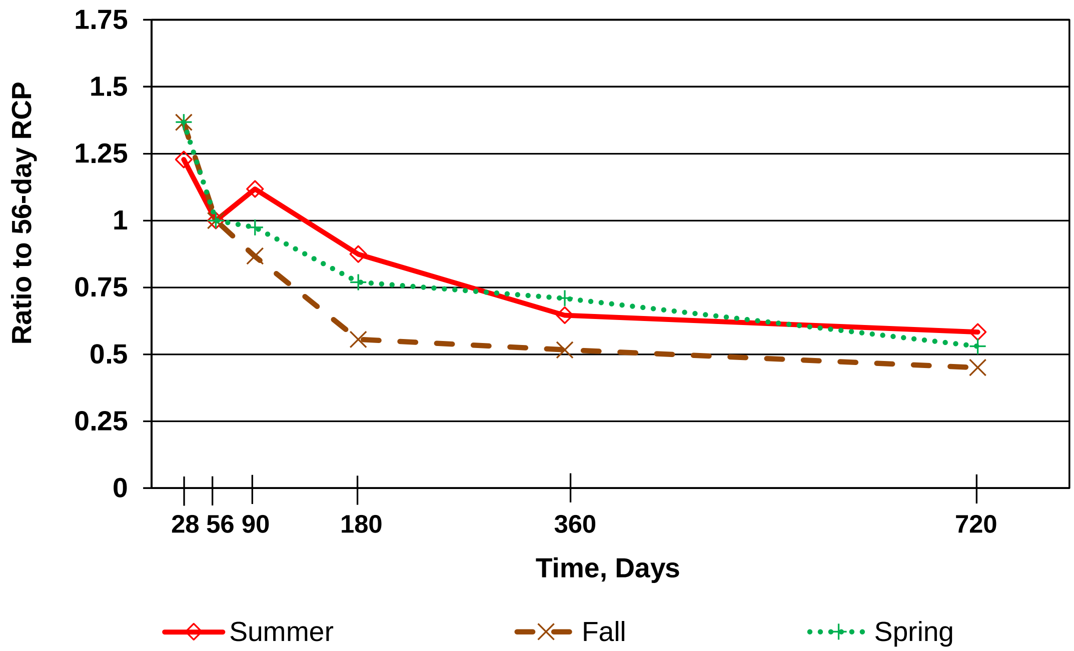

Figure 3.13c: Charge passed in RCP test normalized to values at 56 days for lab-cured cylinders from 60% portland cement/25% slag/15% fly ash (PC/S/FA) mixtures

Figures 3.14a, 3.14b, and 3.14c show the charge passed for the field-cured cylinders normalized to the 56-day values for the 100% portland cement (PC), 65% portland cement/35% slag (PC/S), and 60% portland cement/25% slag/15% fly ash (PC/S/FA) mixtures, respectively. As was the case for lab-cured cylinders, the same general trends were observed across all mixtures, regardless of season. The values at 28 days were generally 25% to 60% greater than those at 56 days, with the rate of decrease slowing over time. The values at 360 days were approximately 75% of those at 56 days, with slightly lower percentages observed in slabs with both slag and fly ash (PC/S/FA).

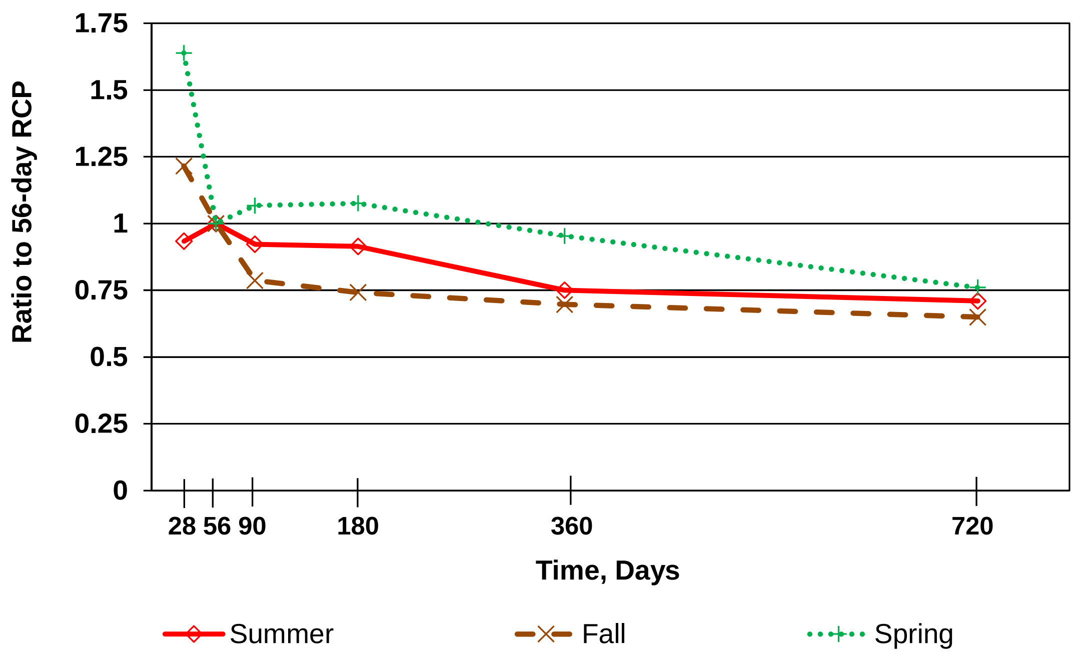

Figure 3.14a: Charge passed in RCP test normalized to values at 56 days for field-cured cylinders from 100% portland cement (PC) mixtures

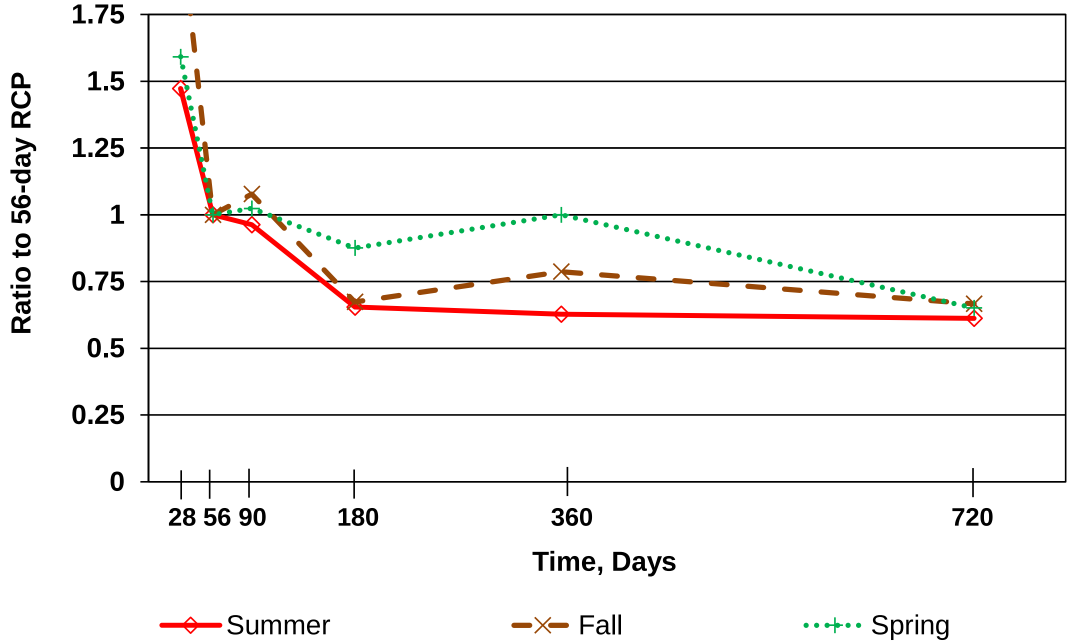

Figure 3.14b: Charge passed in RCP test normalized to values at 56 days for field-cured cylinders from 65% portland cement/35% slag (PC/S) mixtures

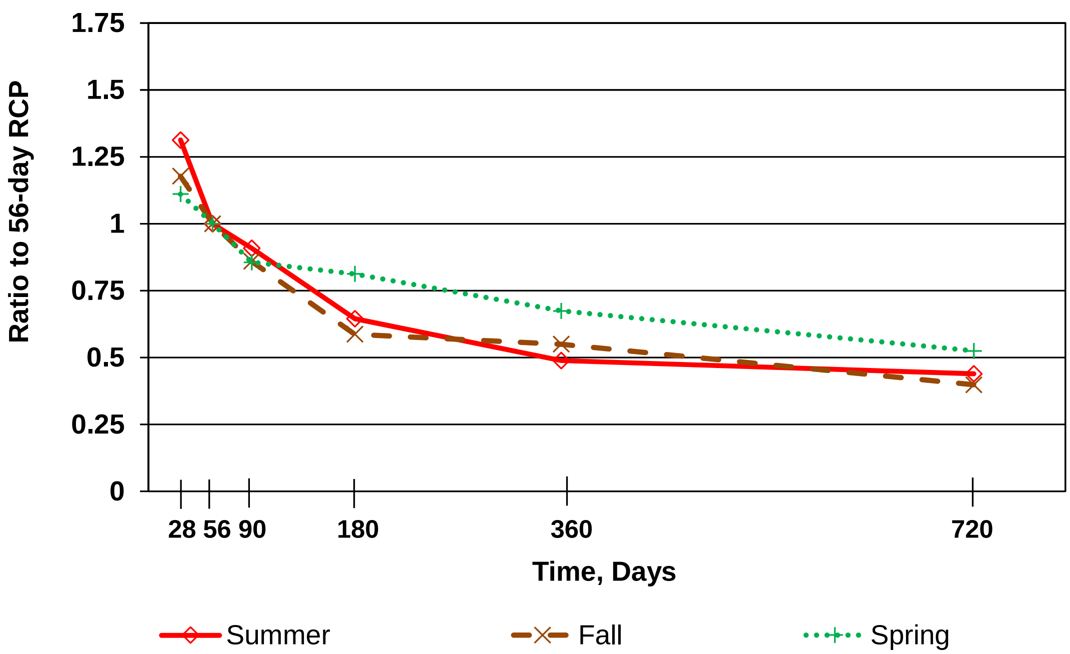

Figure 3.14c: Charge passed in RCP test normalized to values at 56 days for field-cured cylinders from 60% portland cement/25% slag/15% fly ash (PC/S/FA) mixtures

Figures 3.15a, 3.15b, and 3.15c show the charge passed for the cores normalized to the 56-day values for the 100% portland cement (PC), 65% portland cement/35% slag (PC/S) and 60% portland cement/25% slag/15% fly ash (PC/F/FA) mixtures, respectively. Significant variations were observed in charge passed; many specimens exhibited greater charge passed in the RCP test at later ages than at 56 days, likely due to cores with statistically low charges passed being tested at 56 days. The slabs cast in the fall generally had lower values of charge passed at later ages than those cast in spring or summer, suggesting a temperature dependence. This behavior, however, was not observed in field-cured cylinders, which would have been more susceptible to temperature extremes due to their small size. As with lab-cured and field-cured cylinders, the average RCP value for cores at 360 days was about 75% of that found at 56 days, but with significantly greater scatter.

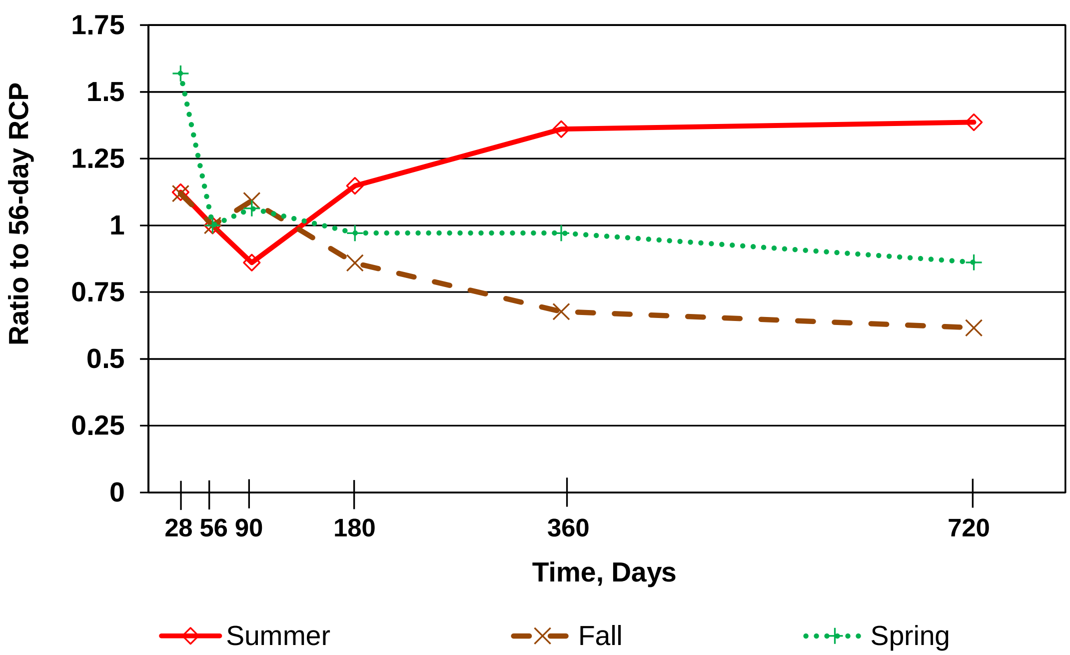

Figure 3.15a: Charge passed in RCP test normalized to values at 56 days for cores from 100% portland cement (PC) mixtures

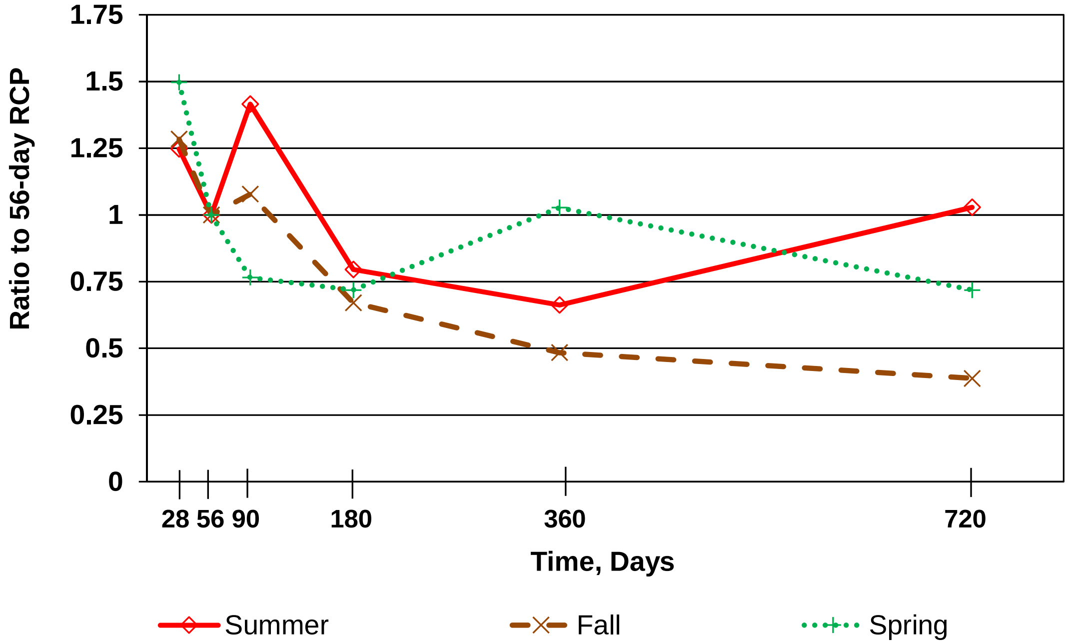

Figure 3.15b: Charge passed in RCP test normalized to values at 56 days for cores from 65% portland cement/35% slag (PC/S) mixtures

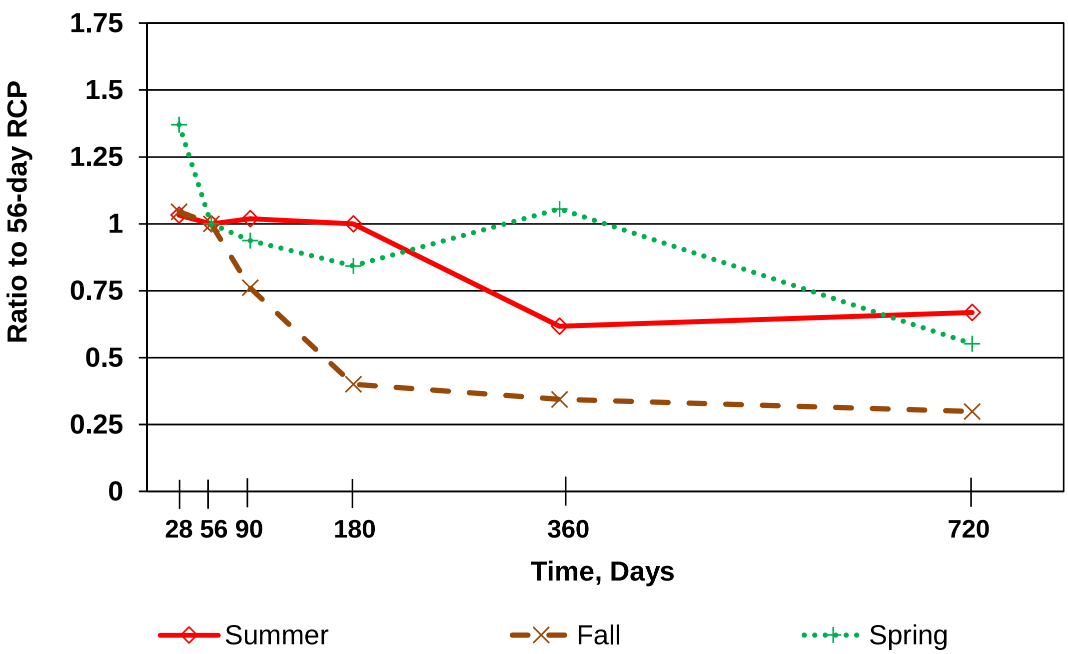

Figure 3.15c: Charge passed in RCP test normalized to values at 56 days for cores from 60% portland cement/25% slag/15% fly ash (PC/S/FA) mixtures

3.2.3 Representative Equations

Table 3.4 summarizes ratios of average charge passed for field-cured cylinders and cores to average charge passed for lab-cured cylinders in the RCP test. The field-cured cylinders exhibited higher RCP values than the cores, but the cores also exhibited a greater range of values, making them less useful than field-cured cylinders as a predictor of charge passed for lab-cured cylinders.

Table 3.4: Ratio of average charge passed for field-cured cylinders and cores to average charge passed for lab-cured cylinders – all specimens at all ages

Specimen	Average	Summer	Fall	Spring	Range
Field-Cured Cylinders	1.56	1.64	1.56	1.50	1.05-2.21
Cores	1.34	1.45	1.39	1.19	0.85-2.48

The ratio of the charge passed for concrete at later ages to the 56-day charge passed, presented in Figures 3.13 and 3.14 (core data were not used in equation development due to the wide scatter relative to 56-day values), may be represented as follows:

For mixtures containing only portland cement, slag cement, or both,

$$Q_t = Q_{56} \times 2.064 t^{-0.18} \tag{3a}$$

t = test age of cylinder, days ($28 \le t \le 720$)

Q_{56} = 56-day charge passed in the RCP test, coulombs

Q_t = charge passed in RCP test at t days, coulombs.

For mixtures containing a minimum of 15% Class C fly ash:

$$Q_t = Q_{56} \times 2.965 t^{-0.27} \tag{3b}$$

Equations (3a) and (3b) were determined, as were Eq. (1a) and (1b), using a least-squares regression analysis to determine the coefficients, with the goal of minimizing the difference between the ratio (in this case, charge passed at time t to 56-day charge passed) predicted by the equation to the ratios found from testing. These comparisons are shown in Figures 3.16a, 3.16b, and 3.16c for mixtures containing 100% portland cement (PC), 65% portland cement/35% slag cement (PC/S), and 60% portland cement/25% slag cement/15% fly ash (PC/S/FA), respectively. Although core data were not used in equation development, they are included in Figures 3.16a, 3.16b, and 3.16c for comparison purposes.

The mean, standard deviation, maximum, and minimum of comparisons of the test results to the values calculated using Eq. (3a) and (3b) are presented in Table 3.5a (excluding cores) and Table 3.5b (including cores). Excluding cores (Table 3.5a), at ages between 28 and 720 days, the mean varies between 0.984 and 1.098, with maximum and minimum values of 1.446 and 0.746 and a COV of 0.155. When core data is included, the COV increases to 0.238. The relatively higher COV [compared with that obtained for Eq. (1a) and (1b)] is primarily due to the 28-day data–the greater variation seen in 28-day data relative to later ages makes accurately fitting a curve difficult. As observed for compressive strength, the wide degree of variation observed in the figures indicates that the behavior of concrete at a particular jobsite may vary from that predicted by Eq. (3a) and (3b), particularly when core data is being analyzed.

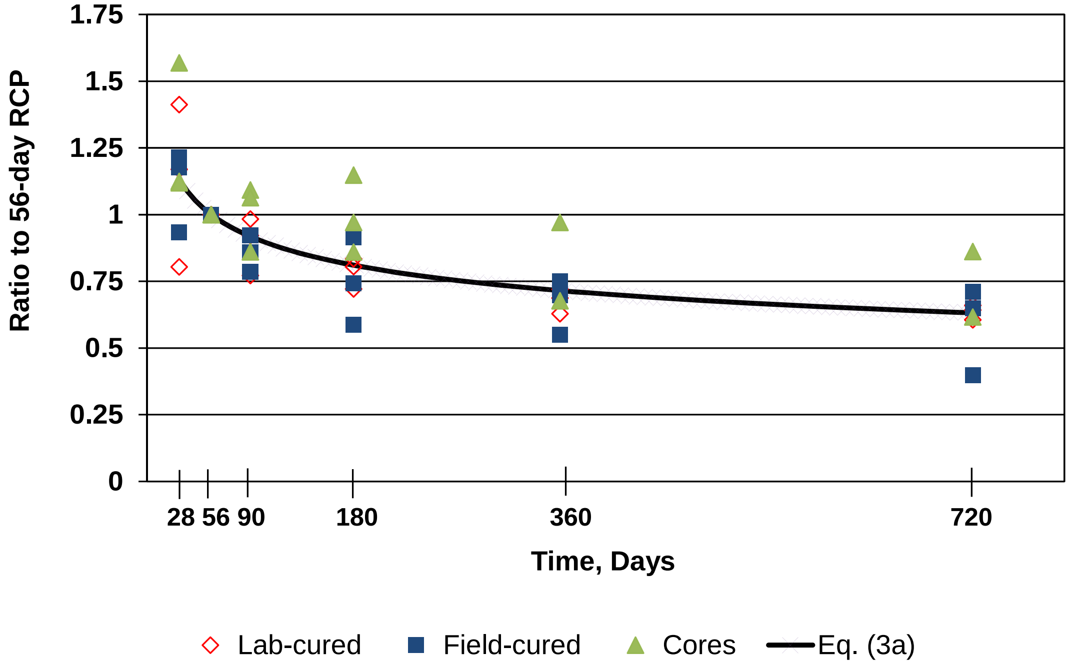

Figure 3.16a: Charge passed in RCP test normalized to values at 56 days and predictive equation for 100% portland cement (PC) mixtures

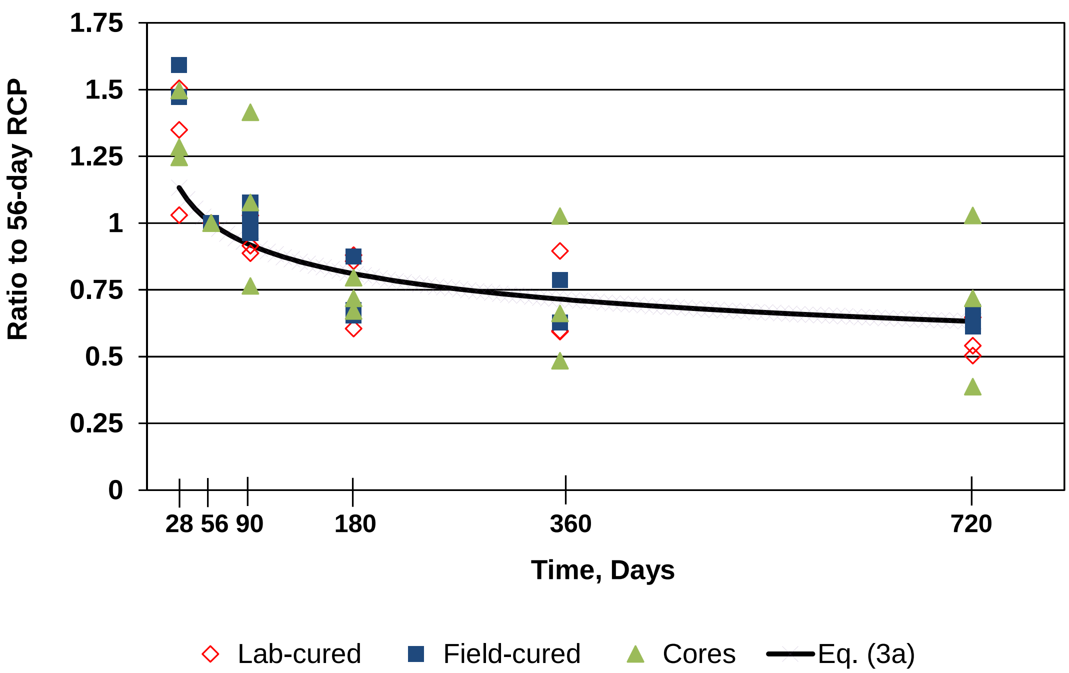

Figure 3.16b: Charge passed in RCP test normalized to values at 56 days and predictive equation for mixtures with 65% portland cement/35% slag (PC/S) cement

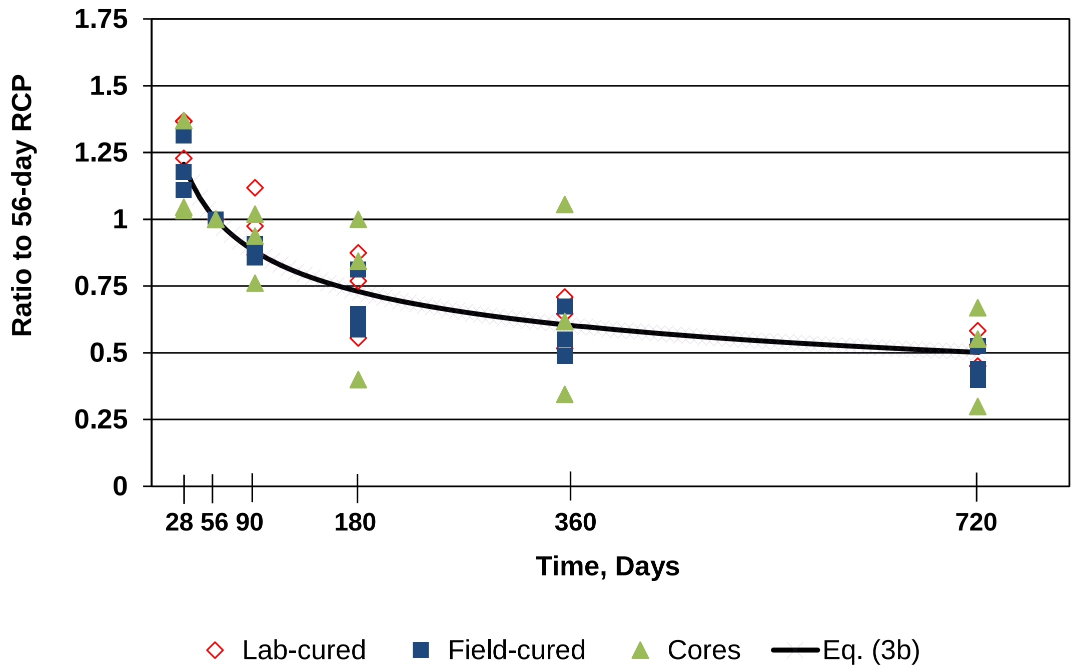

Figure 3.16c: Charge passed in RCP test normalized to values at 56 days and predictive equation for 60% portland cement/25% slag cement/15% fly ash (PC/S/FA) mixtures

Table 3.5a: Statistical parameters for comparisons of test results to values calculated using Eq. (3a) and (3b) (excluding cores)

Age	Average	Standard Deviation	COV	Max	Min
28	1.127	0.182	0.162	1.446	0.825
56	1.000	-	-	-	-
90	1.039	0.108	0.104	1.271	0.841
180	0.984	0.163	0.165	1.327	0.746
360	1.023	0.178	0.174	1.398	0.807
720	0.997	0.116	0.116	1.204	0.794
All	**1.009**	**0.156**	**0.155**	**1.446**	**0.746**

Table 3.5b: Statistical parameters for comparisons of test results to values calculated using Eq. (3a) and (3b) (including cores)

Age	Average	Standard Deviation	COV	Max	Min
28	1.112	0.180	0.162	1.446	0.825
56	1.000	-	-	-	-
90	1.060	0.151	0.142	1.542	0.833
180	1.006	0.204	0.202	1.417	0.548
360	1.074	0.303	0.282	1.902	0.568
720	1.070	0.311	0.290	2.196	0.595
All	**1.042**	**0.238**	**0.229**	**2.196**	**0.548**

Because most RCP test requirements are expressed in terms of the maximum charge passed at 56 days, it is desirable to express Eq. (3a) and (3b) in terms of the estimated 56-day charge passed based on a cylinder tested at a different age.

For mixtures containing only portland cement, slag cement, or both,

$$Q_{56} = Q_t \times 0.4845 t^{0.18} \quad (4a)$$

t = test age of cylinder, days ($28 \le t \le 720$)

Q_{56} = 56-day charge passed in the RCP test, coulombs

Q_t = charge passed in RCP test at t days, coulombs.

For mixtures containing a minimum of 15% Class C fly ash:

$$Q_{56} = Q_t \times 0.3373 t^{0.27} \quad (4b)$$

3.3 BOIL TEST RESULTS (POROSITY)

3.3.1 Comparisons between Cylinders and Cores

Figure 3.17 shows the average permeable free space (voids) at 28 days for the lab-cured cylinders, field-cured cylinders, and cores for each of the nine slabs. Error bars indicate the range in results. For the lab-cured cylinders, seven of the nine slabs had an average percentage of voids below the 12.5% limit specified by KDOT; in all cases, the lab-cured cylinders exhibited a lower percentage of voids than the field-cured cylinders and cores. The field-cured cylinders exhibited a greater percentage of voids than the cores for eight of the nine slabs.

For a given season, the addition of slag cement or slag cement and fly ash generally had no effect on the percentage of voids. One mixture, however, the fall slab containing both slag and fly ash (PC/S/FA), exhibited the highest percentage voids of any mixture in the study. This was likely due to slow hydration from the combination of the use of SCMs and the cold temperatures. For all mixtures, the lowest percentage of voids occurred in the spring slabs, where the concrete temperature was moderate.

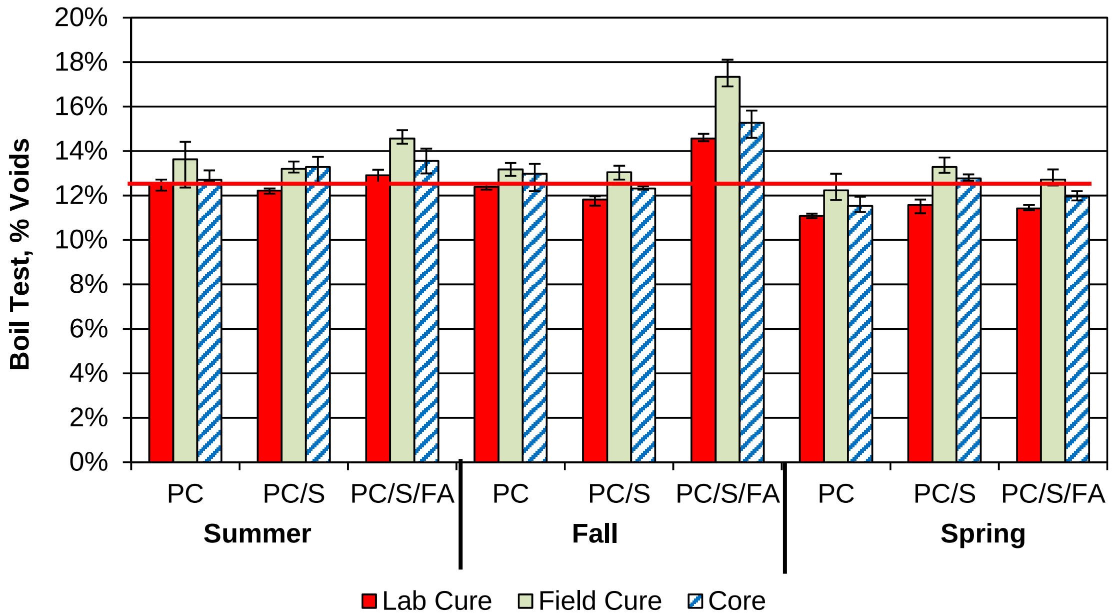

Figure 3.17: Average 28-day boil test results

Figure 3.18 presents the ratio of the percentage of voids measured in the cores to the percentage of voids measured in the matching lab-cured cylinders for all slabs at all ages. A ratio greater than 1 indicates that the average percentage of voids in the cores was greater than the average percentage of voids in lab-cured cylinders at that age. As shown in the figure, cores exhibited a greater percentage of voids than lab-cured cylinders in 51 out of 54 cases, though the differences between values obtained from cores and lab-cured cylinders were small. No clear trends with respect to age or mixture type were observed. On average, the cores exhibited 1.06 times the void content measured in lab-cured cylinders, with a range of 0.84 to 1.19. For all comparisons at all ages, the average ratios were 1.05, 1.06, and 1.07, respectively, for slabs cast in the summer, fall, and spring, indicating no seasonal dependence.

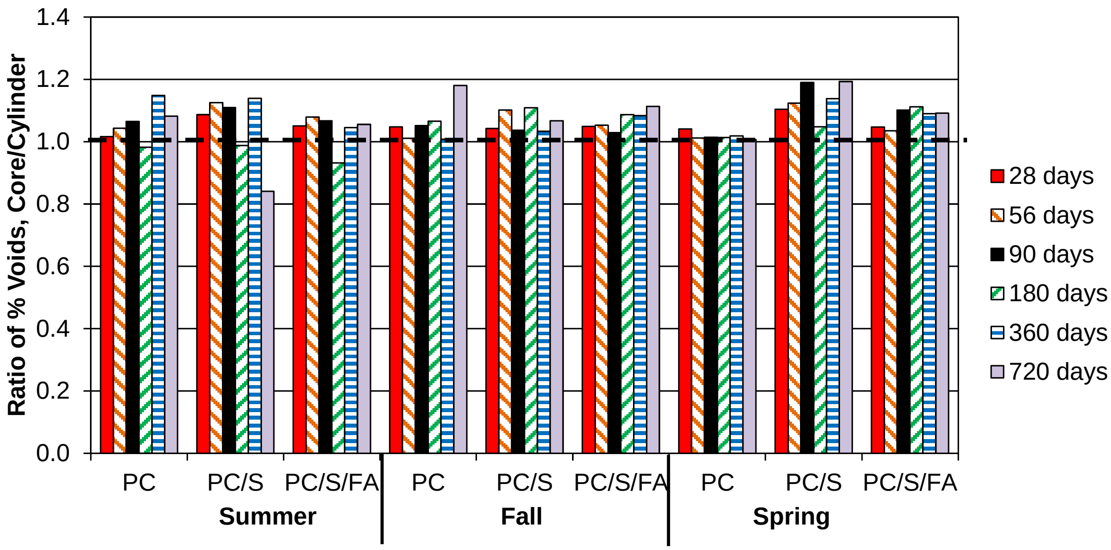

Figure 3.18: Ratio of core percentage voids to lab-cured cylinder percentage voids

Figure 3.19 presents the ratio of the percentage of voids measured in the cores to the percentage of voids measured in the matching field-cured cylinders for all slabs at all ages. The figure shows that the cores exhibited a greater percentage of voids than the field-cured cylinders in just 9 out of 54 cases, although, as was the case with lab-cured cylinders, the differences between values obtained from cores and field-cured cylinders were small. No clear trends with respect to age or mixture type were observed. On average, the cores exhibited 0.96 times the percent of voids measured in lab-cured cylinders, with a range of 0.88 to 1.10. For all comparisons at all ages, the average ratios were 0.95, 0.97, and 0.96, respectively, for slabs cast in the summer, fall, and spring, indicating no seasonal dependence.

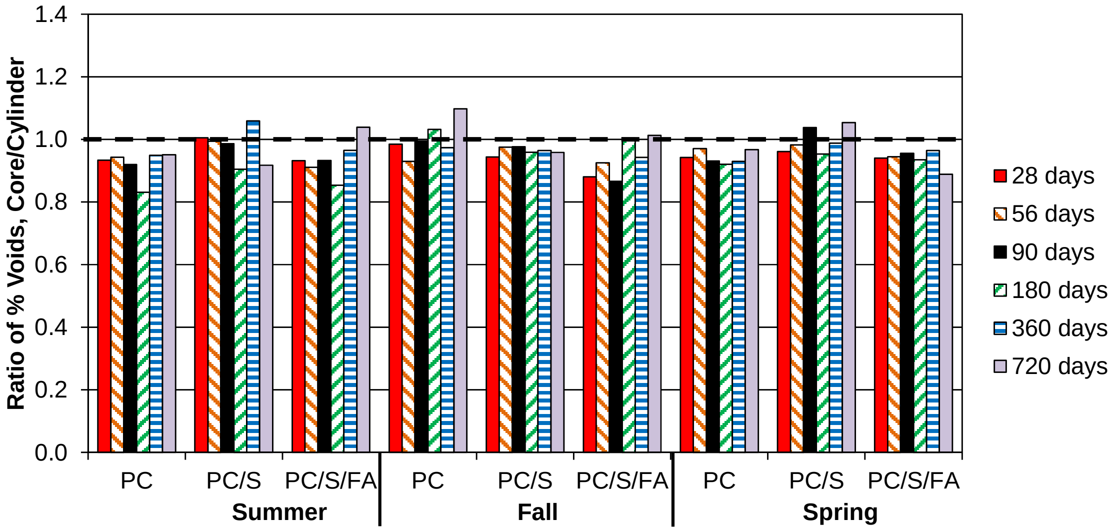

Figure 3.19: Ratio of core percentage voids to field-cured cylinder percentage voids

Figure 3.20 presents the ratio of the percentage of voids measured in the field-cured cylinders to the percentage of voids measured in the lab-cured cylinders for all slabs at all ages. In all but one case, the field-cured cylinders exhibited a greater percentage of voids than the lab-cured cylinders. No clear trends with respect to age or mixture type were observed. On average, the field-cured cylinders exhibited 1.11 times the percent of voids measured in the lab-cured cylinders, with a range of 0.92 to 1.23. For all comparisons at all ages, the average ratios were 1.10, 1.10, and 1.12, respectively, for slabs cast in the summer, fall, and spring, indicating no seasonal dependence.

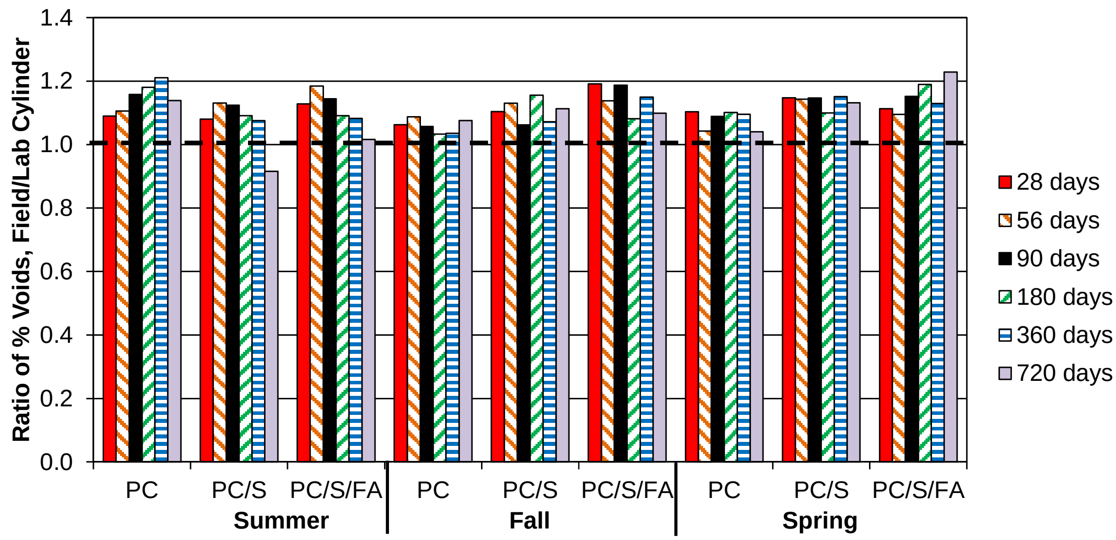

Figure 3.20: Ratio of field-cured cylinder percentage voids to lab-cured cylinder percentage voids

3.3.2 Porosity Variation with Age

Figures 3.21a, 3.21b, and 3.21c show the percentage of voids for *lab-cured cylinders* normalized to the 28-day values for 100% portland cement (PC), 65% portland cement/35% slag (PC/S), and 60% portland cement/25% slag/15% fly ash (PC/S/FA) mixtures, respectively. Although individual readings varied, the same general trends were observed across all mixtures, regardless of season–the percentage of voids exhibited a slight decrease with time. At 720 days, the percentage of voids ranged between 88 and 98 percent of the value at 28 days; for specimens where a decrease occurred, most of the change occurred prior to 90 days. Small, isolated sudden changes in porosity, such as observed from cylinders from the summer slab with 100% portland cement between 28 to 56 days and in cylinders from the spring slab with 60% portland cement, 25% slag cement, and 15% fly ash between 90 and 180 days, are likely due to statistical variation in the samples.

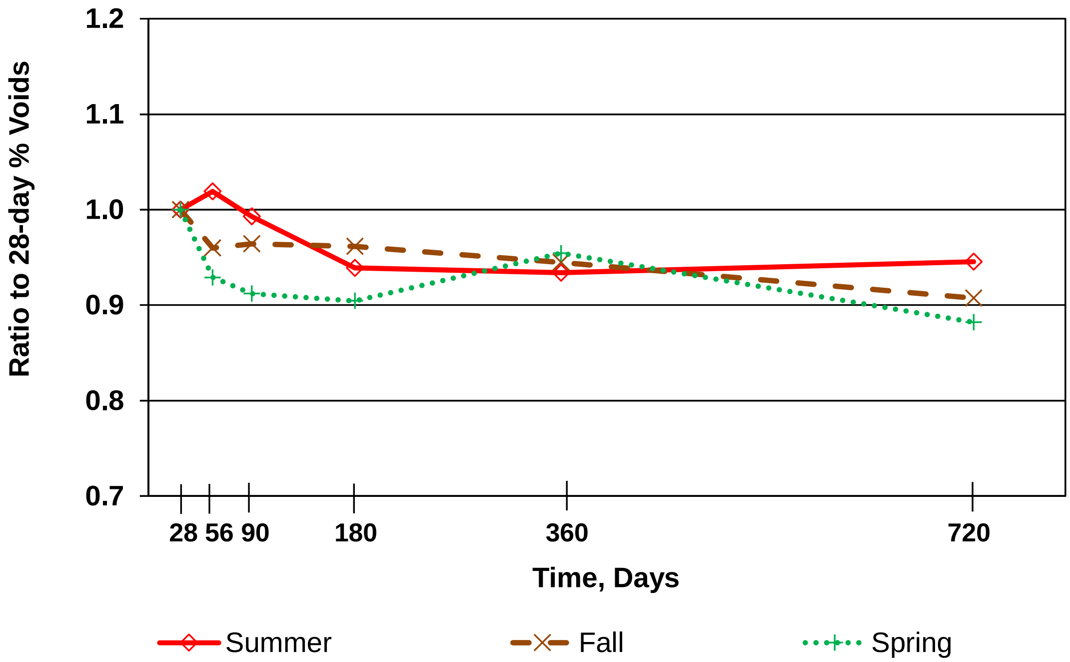

Figure 3.21a: Percentage of voids normalized to values at 28 days for lab-cured cylinders from 100% portland cement (PC) mixtures

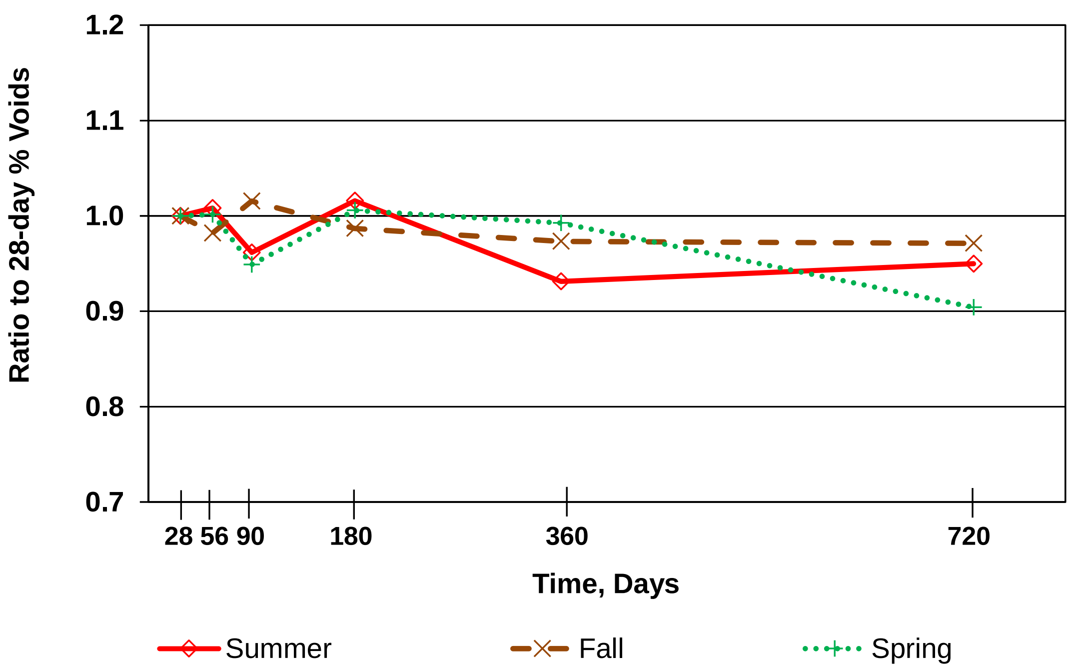

Figure 3.21b: Percentage of voids normalized to values at 28 days for lab-cured cylinders from 65% portland cement/35% slag (PC/S) mixtures

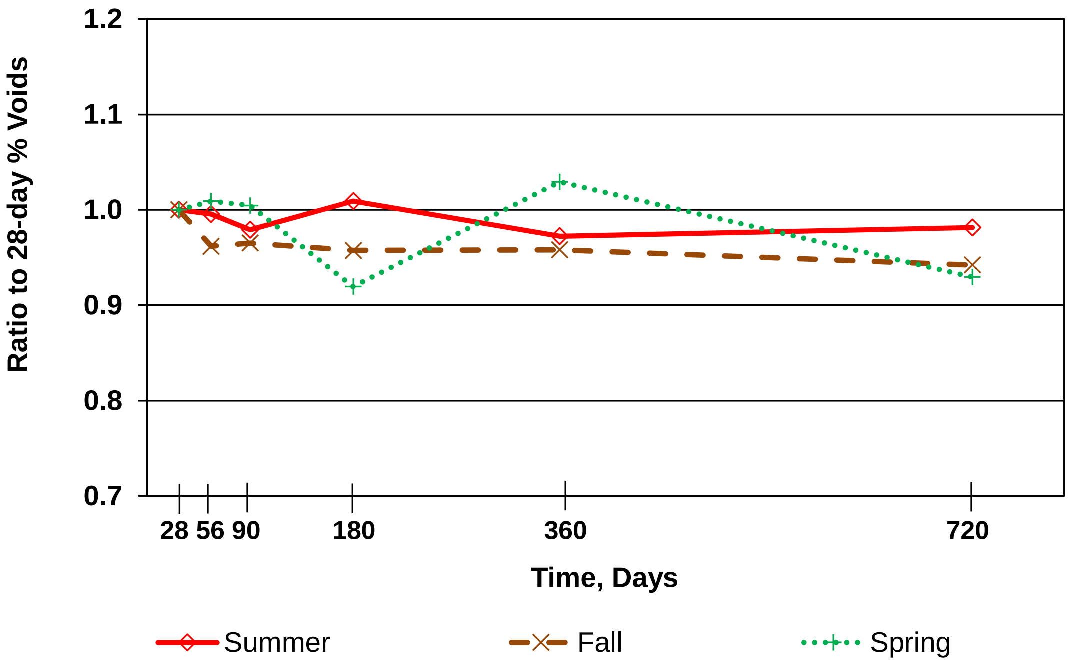

Figure 3.21c: Percentage of voids normalized to values at 28 days for lab-cured cylinders from 60% portland cement/25% slag/15% fly ash (PC/S/FA) mixtures

Figures 3.22a, 3.22b, and 3.22c show the percentage of voids for *field-cured cylinders* normalized to the 28-day values for 100% portland cement (PC), 65% portland cement/35% slag (PC/S), and 60% portland cement/25% slag/15% fly ash (PC/S/FA) mixtures, respectively. A greater degree of scatter was present than was observed for the lab-cured cylinders, but the results still show minimal variation, remaining constant or decreasing slightly with time.

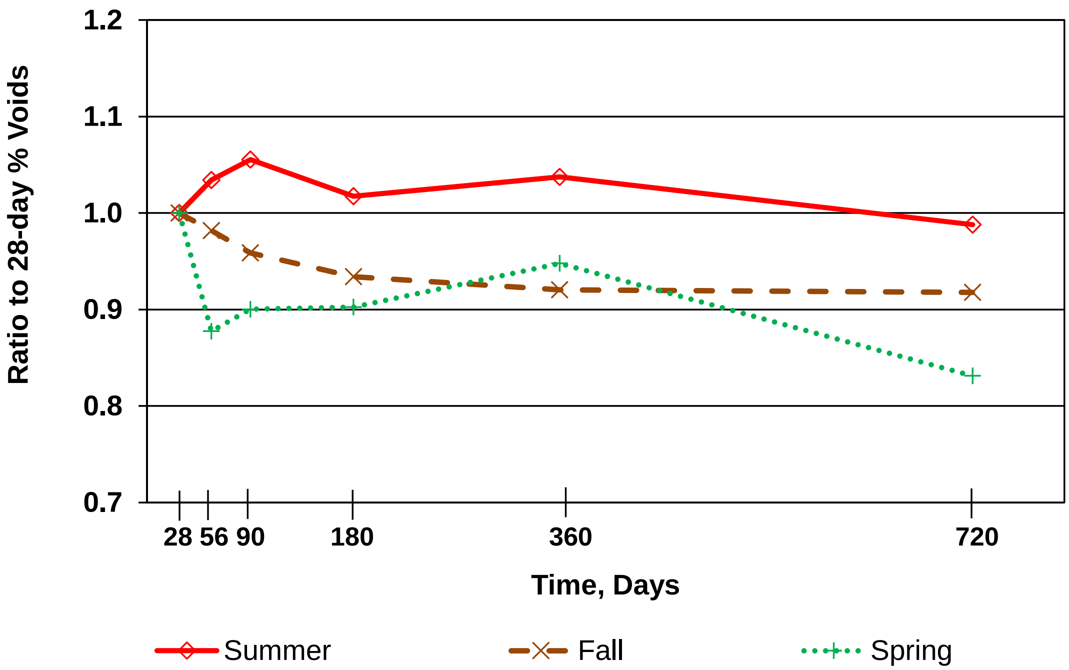

Figure 3.22a: Percentage of voids normalized to values at 28 days for field-cured cylinders from 100% portland cement (PC) mixtures

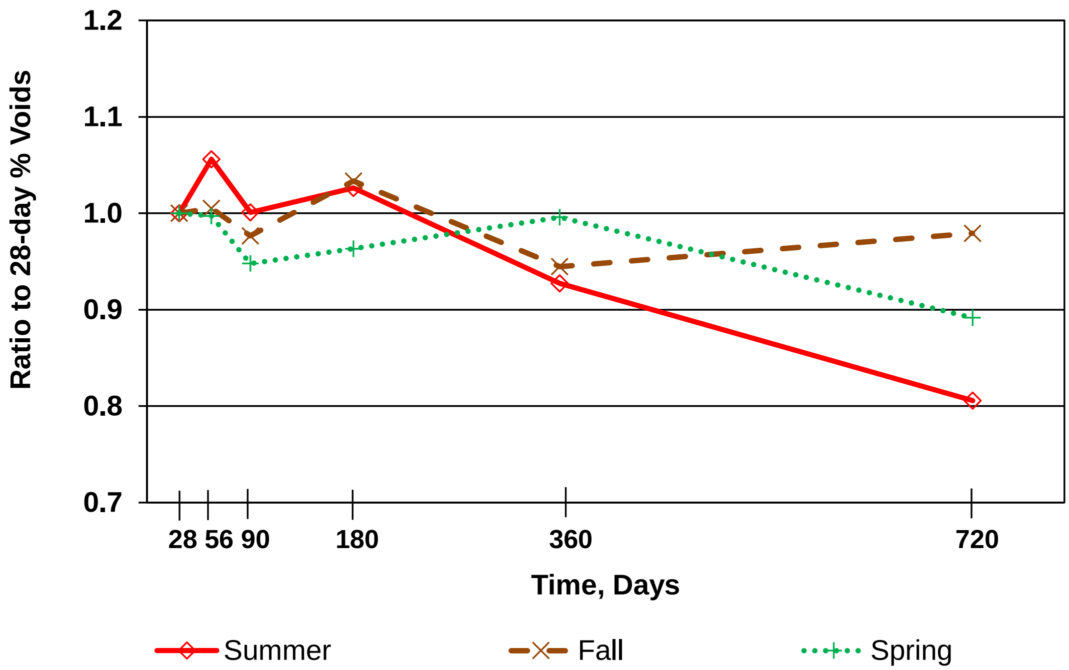

Figure 3.22b: Percentage of voids normalized to values at 28 days for field-cured cylinders from 65% portland cement/35% slag (PC/S) mixtures

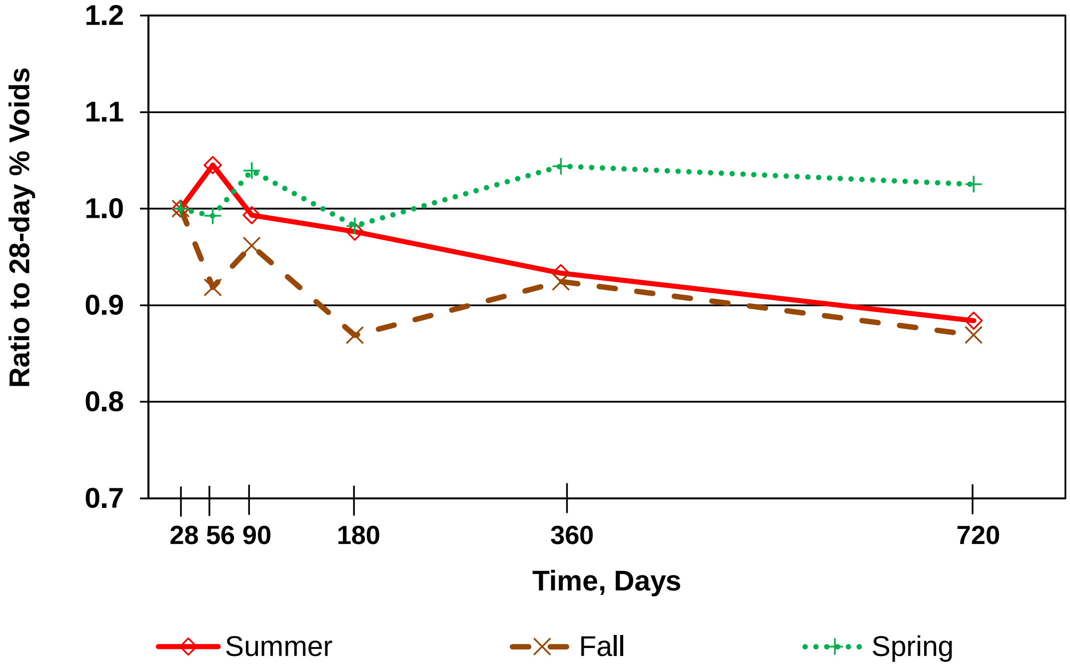

Figure 3.22c: Percentage of voids normalized to values at 28 days for field-cured cylinders from 60% portland cement/25% slag/15% fly ash (PC/S/FA) mixtures

Figures 3.23a, 3.23b, and 3.23c show the percentage of voids for *cores* normalized to the 28-day values for 100% portland cement (PC), 65% portland cement/35% slag (PC/S), and 60% portland cement/25% slag/15% fly ash (PC/S/FA) mixtures, respectively. As was the case for field-cured cylinders, a greater degree of scatter was present than was observed for the lab-cured cylinders, but the results still show minimal variation, remaining constant or decreasing slightly with time. The significant drop in percent voids observed in the summer slab with 65% portland cement/35% slag cement at 720 days is again likely a statistical anomaly.

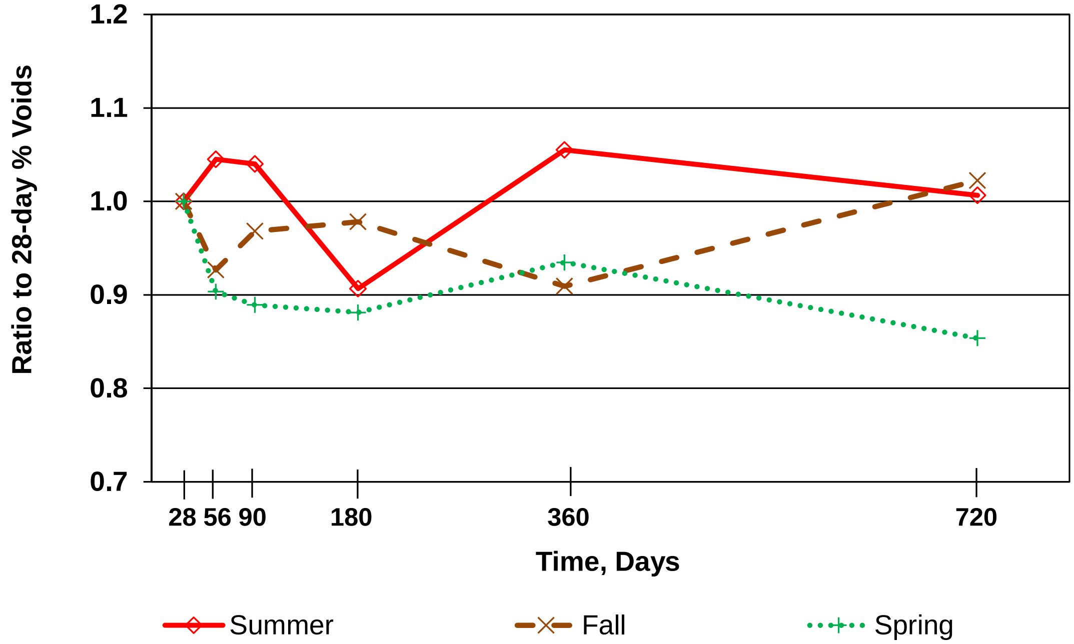

Figure 3.23a: Percentage of voids normalized to values at 28 days for cores from 100% portland cement (PC) mixtures

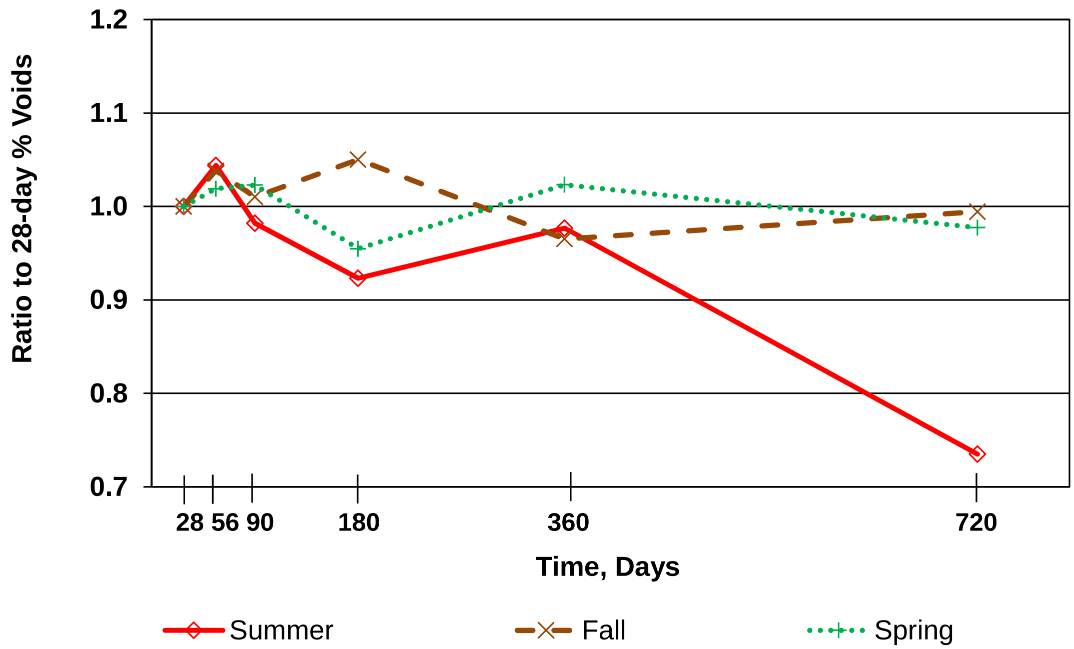

Figure 3.23b: Percentage of voids normalized to values at 28 days for cores from 65% portland cement/35% slag (PC/S) mixtures

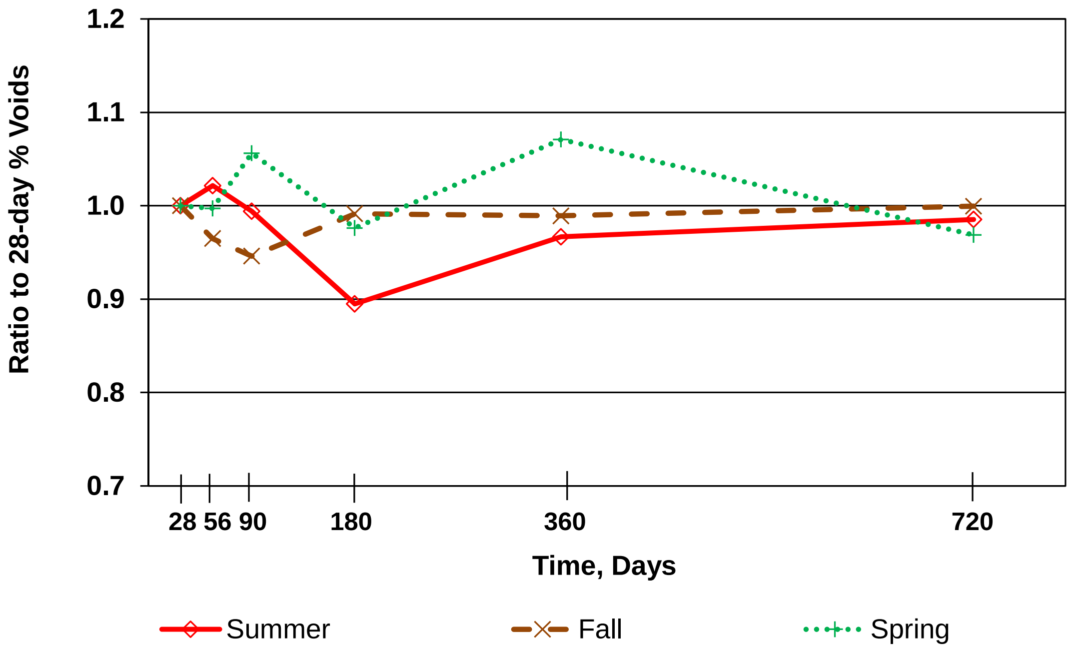

Figure 3.23c: Percentage of voids normalized to values at 28 days for cores from 60% portland cement/25% slag/15% fly ash (PC/S/FA) mixtures

3.3.3 Representative Equations

Table 3.6 summarizes the ratios of percentage of voids in field-cured cylinders and cores to percentage of voids in lab-cured cylinders in the boil test. Much less scatter was observed in the boil test results than in the RCP test results.

Table 3.6: Ratio of percentage of voids in field-cured cylinders and cores to percentage of voids in lab-cured cylinders

Specimen	Average	Summer	Fall	Spring	Range
Field-Cured Cylinders	1.11	1.10	1.10	1.12	0.92-1.23
Cores	1.06	1.05	1.06	1.07	0.84-1.09

The ratio of the percentage of voids at later ages to the percentage of voids at 28 days, presented in Figures 3.21–3.23, may be represented by Eq. (5):

$$P_t = P_{28} \times 1.051 t^{-0.015} \tag{5}$$

t = test age of cylinder, days ($28 \leq t \leq 720$)

P_{28} = percentage voids in the boil test at 28 days

P_t = percentage voids in the boil test result at t days

Equation (5) was determined using a least-squares regression analysis to determine the coefficients, with the goal of minimizing the difference between the ratio (percent voids at time t to percent voids at 28 days) predicted by the equation to the ratios found from testing. These comparisons are shown in Figures 3.24a, 3.24b, and 3.24c for mixtures containing 100% portland cement (PC), 65% portland cement/35% slag cement (PC/S), and 60% portland cement/25% slag cement/15% fly ash (PC/S/FA), respectively.

The mean, standard deviation, maximum, and minimum of comparisons of the test results to the values calculated using Eq. (5) are presented in Table 3.7. At ages between 28 and 720 days, the mean varies between 0.978 and 1.010, with maximum and minimum values of 1.113 and 0.772, respectively. The low overall coefficient of variation, 0.054, indicates that the test data are well represented by Eq. (5). As observed for compressive strength and charge passed, the wide degree of variation observed in the figures indicates that the behavior of concrete at a particular jobsite may vary from that predicted by Eq. (5).

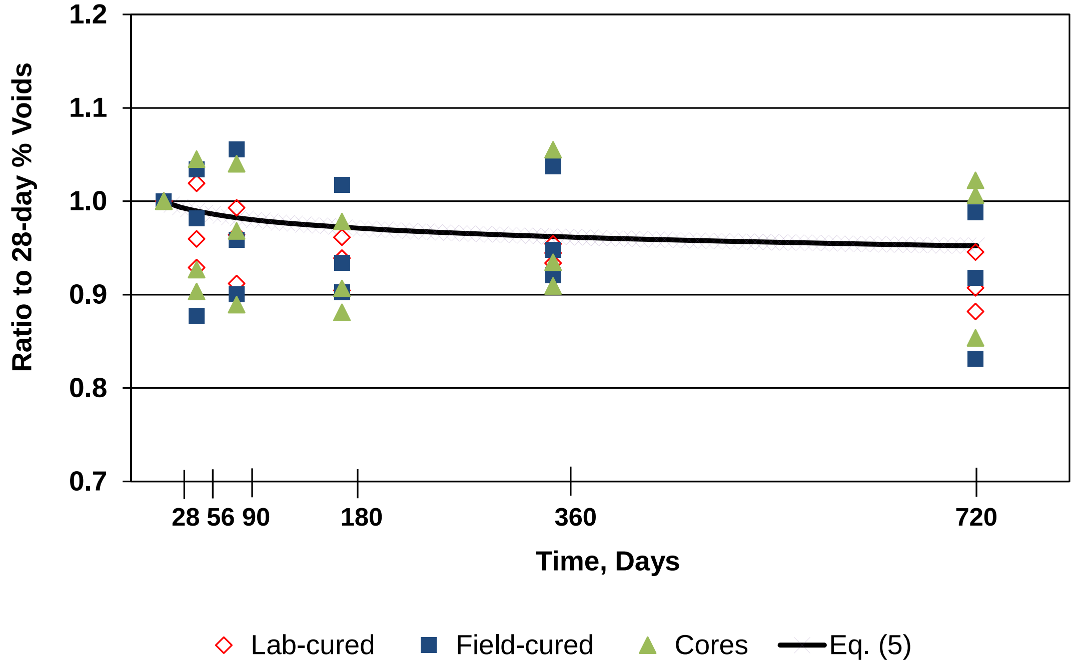

Figure 3.24a: Percent voids normalized to values at 28 days and predictive equation for 100% portland cement (PC) mixtures

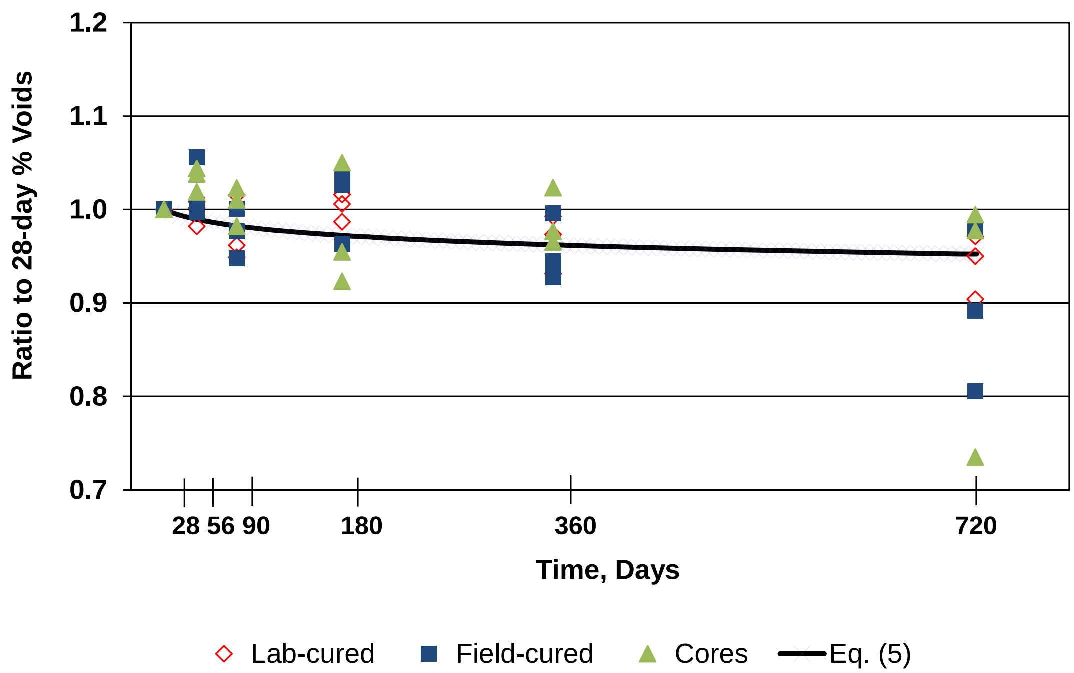

Figure 3.24b: Percent voids normalized to values at 28 days and predictive equation for 65% portland cement/35% slag (PC/S) mixtures

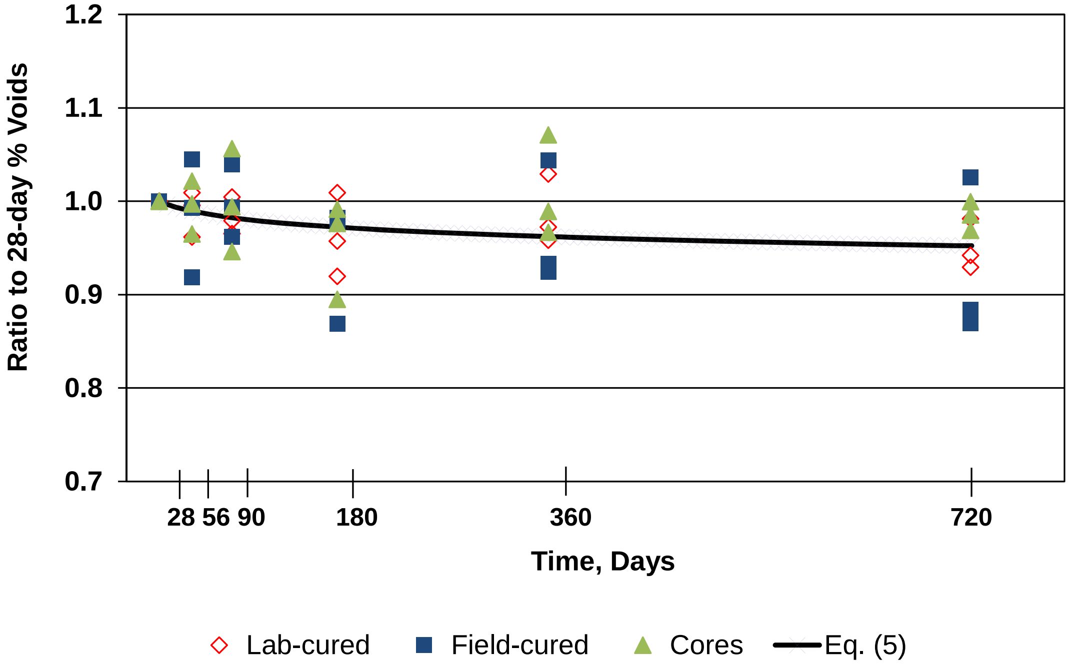

Figure 3.24c: Percent voids normalized to values at 28 days and predictive equation for mixtures with 60% portland cement/25% slag cement/15% fly ash

Table 3.7: Statistical parameters for comparisons of test results to values calculated using Eq. (5)

Age	Average	Standard Deviation	COV	Max	Min
28	1.000	-	-	-	-
56	1.001	0.047	0.047	1.067	0.887
90	0.998	0.044	0.044	1.075	0.905
180	0.989	0.051	0.052	1.080	0.894
360	1.010	0.047	0.046	1.113	0.945
720	0.978	0.074	0.076	1.077	0.772
All	**0.995**	**0.054**	**0.054**	**1.113**	**0.772**

Because most boil test requirements are expressed in terms of a maximum percentage of voids at 28 days, it is desirable to express Eq. (5) in terms of the estimated 28-day percent voids based on a cylinder tested at a different age.

$$P_{28} = P_t \times 0.951 t^{0.015} \tag{6}$$

t = test age of cylinder, days ($28 \leq t \leq 720$)

P_{28} = percentage voids in the boil test at 28 days

P_t = percentage voids in the boil test result at t days

3.4 Comparison between RCP and Boil Test Results

The RCP and boil tests measure different properties of concrete. The RCP test, which measures charge passed under exposure to a chloride solution, is a measure of ion conductivity, while the boil test is a measure of porosity. There is nothing inherent in the two concrete properties measured that would suggest that they are correlated. In spite of this fact, both tests are used to represent concrete quality and to qualify concrete mixtures in the field.

Figure 3.25 presents a comparison between boil test and RCP results for all mixtures at all ages. The KDOT limits of 12.5% voids and 3500 coulombs passed (add reference) are shown for reference. As shown in the figure, there is no correlation between the boil test and RCP results or the limits; many specimens exceeded the 12.5% voids limit in the boil test while exhibiting a charge passed well under the 3500 coulomb limit, and some specimens exceeded the RCP test limit while passing the boil test. This is not surprising given the differences discussed above.

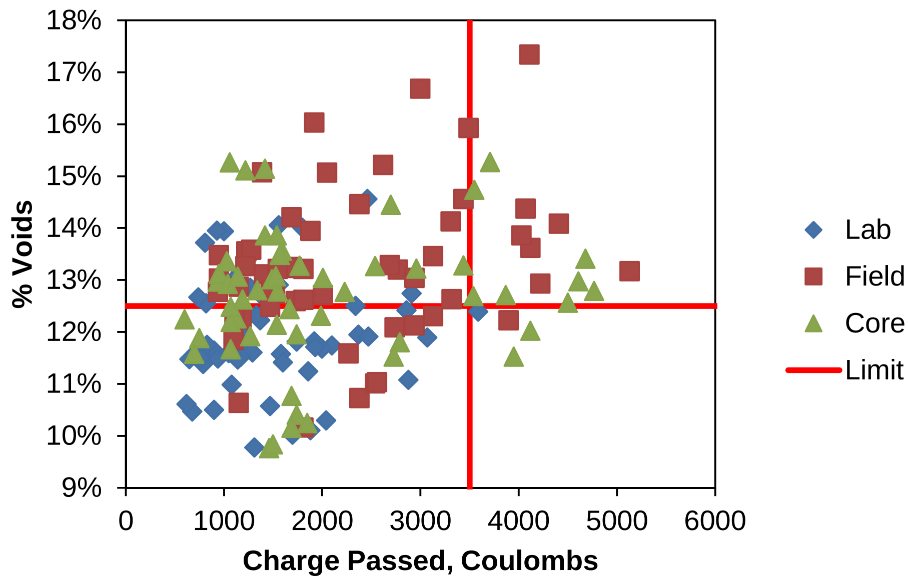

Figure 3.25: Percentage voids versus charge passed for all specimens at all ages.

3.5 Discussion

In many instances, particularly in regards to compressive strength, a large degree of scatter was observed in the results, both for specimens tested at a given age, as demonstrated by the variation in the individual test results shown in Appendix A, and specimens tested at different ages, which presents itself as drops in strength (or increases in permeability or porosity) with time, contrary to expectations. Many factors are likely responsible for this behavior. A significant portion of the scatter observed is due to the natural behavior of concrete; significant variation, including decreases in average compressive strength over time, have been observed in earlier studies (Gray 1990, Lange 1994, Malisch and Suprenant 2013). Although a large number of cylinders were made in the current study, each test was the average of just three cylinders. As a result, an individual test may show results inconsistent with the general trends, particularly at later ages when the changes in concrete properties are relatively small and more likely to be overpowered by statistical variation. Additional variation was also introduced by having multiple personnel molding cylinders for each slab, a necessity given that 122 large number of cylinders were made for each slab. Variations in the degree of consolidation obtained by individual personnel, even though all were certified as ACI Field Testing Technicians – Grade I, could have influenced the results. The procedure, described in Section 2.2, of selecting cylinders for testing from different portions of each batch virtually guaranteed that the specimens tested at a given age would have been prepared by at least two, and perhaps three, individuals. Finally, the relatively low slump (0.75 in.) used in the spring slab with 100% portland cement resulted in difficulties during consolidation of some of the cylinders. Every effort was made to avoid testing cylinders with visible honeycombing, but some of the behavior observed for this slab was likely due to this issue.

CHAPTER 4: SUMMARY

This report details the how concrete compressive strength, permeability, and porosity vary with respect to age at testing, environmental conditions, and curing methods. Three concrete mixtures were included in the study in which the cementitious material consisted of 100% portland cement; 65% portland cement and 35% slag cement; or 60% portland cement, 25% slag cement, and 15% Class C fly ash. Pavement slabs containing each mixture were cast in the summer, fall, and spring, along with companion 4 × 8 in. cylinders, to determine the effect of seasonal variations in environmental conditions on the strength and permeability of the concrete. Compressive strength (ASTM C39), rapid chloride permeability (RCP) (ASTM C1202), and boil (KT-73) tests were performed on lab-cured cylinders, field-cured cylinders, and cores from pavement slabs at ages of 28, 56, 90, 180, 360, and 720 days. A summary of findings and the descriptive equations developed are presented below.

4.1 SUMMARY OF FINDINGS

4.1.1 Comparison of Results (Cylinders vs. Cores)

Across all test methods, lab-cured cylinders exhibited the best performance (highest compressive strength, lowest charge passed in the RCP test, lowest percent voids in the boil test). Generally, the poorest performance was observed in field-cured cylinders, with cores exhibiting performance between that of lab-cured and field-cured cylinders. Elevated air and concrete temperatures resulted in greater differences in compressive strength between lab-cured and field-cured cylinders; the role of temperature on differences between lab-cured and field-cured cylinders in the other two tests was less clear. Field-cured cylinders and cores tended to exhibit a greater variation in test results than lab-cured cylinders. This was particularly evident in the RCP test results from cores.

The good performance of the lab-cured specimens relative to the others is readily explained by the curing environment. Lab-cured cylinders are exposed to moderate temperatures and high humidity, providing ideal conditions for hydration. Field-cured cylinders and cores experience wide fluctuations in temperature and are likely to dry out, slowing or halting hydration. The large mass of the slab results in slower increases and decreases in temperature and moisture than experienced by the field-cured cylinders, explaining the better performance of cores relative to the field-cured cylinders.

4.1.2 Effect of Season

Generally speaking, specimens cast in the spring, when temperatures were moderate, exhibited better performance than those cast in the summer or fall. The high summer temperatures were particularly disadvantageous to the mixture containing 100% portland cement; the summer slab with 100% portland cement exhibited lower compressive strength and a higher percentage of voids than the same mixture cast in either the fall or spring. Conversely, mixtures containing slag cement or slag cement and Class C fly ash exhibited poorer performance when cast in the fall, particularly the mixture containing slag and fly ash. These differences are likely due to differences in the nature and rate of hydration between the mixtures. The mixture containing slag and fly ash, which will hydrate more slowly and generate less heat than portland cement alone, saw low early-age performance when outside temperatures were colder, but was relatively unharmed in higher temperatures.

4.2 DESCRIPTIVE EQUATIONS

4.2.1 Specimen Type

Tables 4.1–4.3 summarize the relationships between field-cured cylinder and core test results and the lab-cured cylinder test results. Due to the wide variation in the RCP results from cores, it is recommended that cores not be used as a stand-in for lab-cured RCP results.

Table 4.1: Ratio of strength of field-cured cylinders and cores to strength of lab-cured cylinders

Specimen	Average	Summer	Fall	Spring	Range
Field-Cured Cylinders	0.89	0.83	0.94	0.91	0.69 to 1.13
Cores	0.94	0.91	0.97	0.94	0.79 to 1.26

Table 4.2: Ratio of charge passed by specimens from field-cured cylinders and cores to charge passed by specimens from lab-cured cylinders in RCP test

Specimen	Average	Summer	Fall	Spring	Range
Field-Cured Cylinders	1.56	1.64	1.56	1.50	1.05-2.21
Cores	1.34	1.45	1.39	1.19	0.85-2.48

Table 4.3: Ratio of percentage voids in field-cured cylinders and cores to percentage voids in lab-cured cylinders

Specimen	Average	Summer	Fall	Spring	Range
Field-Cured Cylinders	1.11	1.10	1.10	1.12	0.92-1.23
Cores	1.06	1.05	1.06	1.07	0.84-1.09

4.2.2 Specimen Age

Equations (2), (4), and (6) (introduced in Chapter 3 and reproduced in this chapter) relate the results from a test performed at a non-standard age to the expected value at the standard test age (28 days for compressive strength and boil tests; 56 days for the RCP test).

4.2.2.1 Compressive Strength

Equations (2a) and (2b) express the 28-day compressive strength for a given sample type as a function of the compressive strength measured at a later age.

For mixtur3es containing portland only cement, slag cement, or both:

$$\sigma_{28} = \frac{\sigma_t}{0.08\ \ln(t) + 0.733} \tag{2a}$$

t = test age of cylinder, days ($28 \leq t \leq 360$)

σ_{28} = predicted 28-cylinder (or core) compressive strength, and

σ_t = cylinder (or core) compressive strength at time t.

For $360 \leq t \leq 720$, use $t = 360$ in Eq. (2a).

For mixtures containing a minimum of 15% Class C fly ash,

$$\sigma_{28} = \frac{\sigma_t}{\alpha \ln(t) + \beta} \tag{2b}$$

t = test age of cylinder, days ($28 \leq t \leq 720$)

α, β = as defined in Table 4.4

Table 4.4: *α* and β values for use in Eq. (2b)

	Mixtures Containing 15% Class C Fly Ash		**Other Cases**	
Specimen Type	**α**	**β**	**α**	**β**
Lab-Cured Cylinder	0.08	0.733	0.08	0.733
Field-Cured Cylinder	0.145	0.517	0.08	0.733
Core	0.10	0.667	0.08	0.733

4.2.2.2 Rapid Chloride Permeability (RCP)

Equations (4a) and (4b) express the charge passed in the 56-day RCP test as a function of test results obtained between 28 and 720 days.

For mixtures containing only portland cement, slag cement, or both,

$$Q_{56} = Q_t \times 0.4845 t^{0.18} \tag{4a}$$

t = test age of cylinder, days ($28 \leq t \leq 720$)

Q_{56} = 56-day charge passed in the RCP test, coulombs

Q_t = charge passed in RCP test at t days, coulombs.

For mixtures containing a minimum of 15% Class C fly ash:

$$Q_{56} = Q_t \times 0.3373t^{0.27} \tag{4b}$$

4.2.2.3 Boil Test

Equation (6) expresses the percentage voids measured at 28 days in the boil test as a function of test results obtained between 28 and 720 days.

$$P_{28} = P_t \times 0.951t^{0.015} \tag{6}$$

t = test age of cylinder, days ($28 \leq t \leq 720$)

P_{28} = percentage voids in the boil test at 28 days

P_t = percentage voids in the boil test result at t days

4.3 CONCLUSIONS

The following conclusions are based on the results and analyses presented in this report.

1. Concrete cast in moderate temperatures (spring) exhibited higher compressive strengths, a lower charge passed in the RCP test, and a lower percentage of voids in the boil test than concrete placed in high or low temperatures. The use of slag cement or slag cement and Class C fly ash as partial replacements for portland cement lessened the negative impact of high temperatures on these properties, but was detrimental to the early age properties of concrete cast in cold temperatures.
2. Lab-cured cylinders exhibit higher compressive strengths, a lower charge passed in the RCP test, and a lower percentage of voids in the boil test than field-cured cylinders or cores.

3. The equations presented in this report provide reasonable predictors for the variation of the concrete properties studied over time.
4. In general, no correlation exists between percentage of voids in the boil test and the charge passed in the RCP test.

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APPENDIX A: INDIVIDUAL TEST RESULTS

Table A.1: Strength Data (psi), Summer Slab, 100% PC

Age	Sample Type	Sample 1	Sample 2	Sample 3	Average
28 day	Lab	4340	4730	4410	4490
	Field	3740	4320	4430	4160
	Core	4670	4170	4060	4300
56 day	Lab	5190	5780	5310	5430
	Field	4280	5320	4750	4780
	Core	4800	4660	5020	4830
90 day	Lab	5110	5580	5570	5420
	Field	4530	4390	5070	4660
	Core	5780	5110	5020	5300
180 day	Lab	5570	4930	5150	5220
	Field	3440	4330	3920	3900
	Core	3890	3670	4820	4130
360 day	Lab	5870	5950	5880	5900
	Field	5500	5990	4740	5410
	Core	5390	4520	4910	4940
720 day	Lab	5570	6210	5410	5730
	Field	5490	5170	4380	5010
	Core	4990	5130	5240	5120

Table A.2: Strength Data (psi), Summer Slab, 65% PC/35% S

Age	Sample Type	Sample 1	Sample 2	Sample 3	Average
28 day	Lab	4850	6010	5970	5610
	Field	4160	4750	4990	4630
	Core	4150	5740	4770	4890
56 day	Lab	6230	5560	5550	5780
	Field	4380	5360	4950	4900
	Core	5780	6090	6100	5990
90 day	Lab	6050	6030	6250	6110
	Field	4040	4660	4020	4240
	Core	5670	5220	5310	5400
180 day	Lab	5480	6260	6710	6150
	Field	4450	4810	3890	4380
	Core	5180	5560	5120	5290
360 day	Lab	6580	7090	6590	6750
	Field	5820	6490	6620	6310
	Core	6260	6220	6880	6450
720 day	Lab	6270	6550	7010	6610
	Field	5250	5730	6080	5690
	Core	5810	5870	5750	5810

Table A.3: Strength Data (psi), Summer Slab, 60% PC/25% S/15% FA

Age	Sample Type	Sample 1	Sample 2	Sample 3	Average
28 day	Lab	5120	5230	5140	5160
	Field	3780	4390	4040	4070
	Core	5630	5020	4850	5170
56 day	Lab	5150	4990	5450	5200
	Field	3770	4770	4090	4210
	Core	4310	4650	5850	4940
90 day	Lab	5640	5760	5130	5510
	Field	4270	4850	4950	4690
	Core	4790	5170	4890	4950
180 day	Lab	5640	5770	5860	5760
	Field	4190	5200	4570	4650
	Core	4310	4870	5200	4790
360 day	Lab	6430	6980	6830	6750
	Field	4810	6050	6060	5640
	Core	6460	5970	6670	6370
720 day	Lab	6740	6780	6220	6580
	Field	5850	5070	6130	5680
	Core	5320	6320	6710	6120

Table A.4: Strength Data (psi), Fall Slab, 100% PC

Age	Sample Type	Sample 1	Sample 2	Sample 3	Average
28 day	Lab	5320	5240	5130	5230
	Field	5050	5250	4160	4820
	Core	4870	5130	4190	4730
56 day	Lab	5820	5740	5240	5600
	Field	5070	5240	5810	5370
	Core	5230	5330	4980	5180
90 day	Lab	5380	6250	4970	5530
	Field	5370	5160	5170	5230
	Core	4750	4160	5060	4660
180 day	Lab	5690	6090	6600	6130
	Field	6090	6090	6170	6120
	Core	4690	6480	6290	5820
360 day	Lab	6110	6830	6810	6580
	Field	5410	6400	5800	5870
	Core	5420	5560	5950	5640
720 day	Lab	6690	5970	6350	6340
	Field	7270	6680	7090	7010
	Core	6110	6160	6140	6140

Table A.5: Strength Data (psi), Fall Slab, 65% PC/35% S

Age	Sample Type	Sample 1	Sample 2	Sample 3	Average
28 day	Lab	4950	5880	5510	5450
	Field	5310	5990	5760	5690
	Core	5870	5600	5200	5560
56 day	Lab	6470	6080	6520	6360
	Field	5760	6320	5240	5770
	Core	6840	5200	6050	6030
90 day	Lab	6930	6840	6170	6650
	Field	5860	6130	6140	6040
	Core	6590	6180	6250	6340
180 day	Lab	7360	7360	7290	7340
	Field	6560	7180	6600	6780
	Core	6760	5940	7100	6600
360 day	Lab	6860	6630	6850	6780
	Field	6080	6890	6930	6630
	Core	6450	7360	8140	7320
720 day	Lab	5500	6680	6660	6280
	Field	6330	6870	5560	6250
	Core	6670	8820	8400	7960

Table A.6: Strength Data (psi), Fall Slab, 60% PC/25% S/15% FA

Age	Sample Type	Sample 1	Sample 2	Sample 3	Average
28 day	Lab	4650	4150	4340	4380
	Field	3760	4010	2640	3470
	Core	3880	4140	4180	4070
56 day	Lab	4900	5090	5120	5040
	Field	4330	3950	4650	4310
	Core	4840	4290	4230	4450
90 day	Lab	5250	5630	4980	5290
	Field	3940	4020	4380	4110
	Core	4750	3790	4650	4400
180 day	Lab	4890	4730	5400	5010
	Field	4220	5050	4800	4690
	Core	4500	5420	5530	5150
360 day	Lab	4640	4480	5140	4750
	Field	5340	5360	5470	5390
	Core	5420	5850	5440	5570
720 day	Lab	5690	6330	6360	6130
	Field	6020	6220	4900	5710
	Core	6080	6190	6360	6210

Table A.7: Strength Data (psi), Spring Slab, 100% PC

Age	Sample Type	Sample 1	Sample 2	Sample 3	Average
28 day	Lab	6950	6480	6900	6780
	Field	7160	7320	6460	6980
	Core	6270	5300	5710	5760
56 day	Lab	6950	7360	6260	6860
	Field	7490	7060	5570	6710
	Core	5650	6590	7070	6440
90 day	Lab	7100	7010	7410	7170
	Field	7370	6820	7060	7080
	Core	6320	7530	7530	7130
180 day	Lab	8740	8120	5210	7360
	Field	6740	6510	6820	6690
	Core	7580	7210	7220	7340
360 day	Lab	7730	8570	7280	7860
	Field	6360	6700	7550	6870
	Core	7990	8010	8090	8030
720 day	Lab	6180			6180
	Field	7110	6180	5850	6380
	Core	6080	6860	5950	6300

Table A.8: Strength Data (psi), Spring Slab, 65% PC/35% S

Age	Sample Type	Sample 1	Sample 2	Sample 3	Average
28 day	Lab	5610	6110	6660	6130
	Field	5170	5200	5440	5270
	Core	5920	5790	5130	5610
56 day	Lab	5860	6070	6700	6210
	Field	5970	6540	5490	6000
	Core	6040	5550	5480	5690
90 day	Lab	6860	6780	6750	6800
	Field	5490	5840	5990	5770
	Core	6120	6030	5430	5860
180 day	Lab	7370	7370	7450	7400
	Field	5790	6300	5940	6010
	Core	6290	6700	6530	6510
360 day	Lab	7670	7270	6350	7100
	Field	5620	6810	5950	6130
	Core	7320	7430	7660	7470
720 day	Lab	6730	8080	6900	7240
	Field	6590	5820	6400	6270
	Core	5950	6690	6170	6270

Table A.9: Strength Data (psi), Spring Slab, 60% PC/25% S/15% FA

Age	Sample Type	Sample			Average
		1	2	3	
28 day	Lab	4990	5610	5870	5490
	Field	5020	4890	5440	5120
	Core	5670	4870	4830	5120
56 day	Lab	5720	5810	6310	5950
	Field	5550	5080	5160	5260
	Core	5570	6250	5140	5650
90 day	Lab	6400	5590	7010	6330
	Field	5400	6360	5790	5850
	Core	6650	5240	6100	6000
180 day	Lab	6900	6890	6080	6620
	Field	5830	5280	5790	5630
	Core	5360	6810	5650	5940
360 day	Lab	7090	6420	5660	6390
	Field	5870	6330	5800	6000
	Core	6220	6540	6150	6300
720 day	Lab	7770	6830	7520	7370
	Field	7510	7210	7660	7460
	Core	7310	7130	5620	6690

Table A.10: RCP Test Data (coulombs), Summer Slab, 100% PC

Age	Sample Type	Sample			Average
		1	2	3	
28 day	Lab	2533	2780	1719	2340
	Field	4026	4199	4127	4120
	Core	4065	4012	3522	3870
56 day	Lab	3028	2930	2777	2910
	Field	4661	5375	3182	4410
	Core	4426	3443	2444	3440
90 day	Lab	2403	2439	2747	2530
	Field	3850	4216	4158	4070
	Core	2061	3662	3163	2960
180 day	Lab	2233	1871	2197	2100
	Field	3543	4762	3775	4030
	Core	3990	4467	3408	3950
360 day	Lab	-	1854	2142	2000
	Field	3614	3311	3018	3310
	Core	5026	5019	4003	4680
720 day	Lab	1880	1952	1923	1920
	Field	2770	3610	3007	3130
	Core	4955	4664	4677	4770

Table A.11: RCP Test Data (coulombs), Summer Slab, 65% PC/35% S

Age	Sample Type	Sample			Average
		1	2	3	
28 day	Lab	1484	1486	1128	1370
	Field	2852	2774	2696	2770
	Core	2358	1487	1474	1770
56 day	Lab	1310	1467	1198	1330
	Field	1634	1979	2131	1880
	Core	1367	1487	1404	1420
90 day	Lab	1165	1186	1190	1180
	Field	1822	1783	1839	1810
	Core	1440	2144	2431	2010
180 day	Lab	1193	1223	1100	1170
	Field	1279	1194	1223	1230
	Core	1054	981	1360	1130
360 day	Lab	795	778	795	790
	Field	1167	1194	1165	1180
	Core	815	1237	757	940
720 day	Lab	526	867	774	720
	Field	1210	1138	1090	1150
	Core	1090	1748	1552	1460

Table A.12: RCP Test Data (coulombs), Summer Slab, 60% PC/25% S/15% FA

Age	Sample Type	Sample			Average
		1	2	3	
28 day	Lab	1657	1767	1251	1560
	Field	3145	4063	3115	3440
	Core	1506	1830	1434	1590
56 day	Lab	1078	1356	1364	1270
	Field	2791	2643	2431	2620
	Core	1332	1675	1616	1540
90 day	Lab	1293	1513	1466	1420
	Field	2594	2435	2117	2380
	Core	1622	1925	1515	1690
180 day	Lab	959	1053	1306	1110
	Field	1892	1616	1550	1690
	Core	1594	1558	1458	1540
360 day	Lab	888	829	729	820
	Field	1542	1278	1024	1280
	Core	1127	863	853	950
720 day	Lab	724	792	717	740
	Field	1016	1097	1343	1150
	Core	1156	1036	911	1030

Table A.13: RCP Test Data (coulombs), Fall Slab, 100% PC

Age	Sample Type	Sample 1	Sample 2	Sample 3	Average
28 day	Lab	2965	3865	3926	3590
	Field	4504	5523	5353	5130
	Core	4681	4521	4623	4610
56 day	Lab	2922	3156	3145	3070
	Field	3805	4489	4358	4220
	Core	4025	4063	4262	4120
90 day	Lab	2287	2413	2411	2370
	Field	3324	3599	3026	3320
	Core	4599	4587	4304	4500
180 day	Lab	2641	2490	2267	2470
	Field	3071	3327	2982	3130
	Core	3687	3630	3302	3540
360 day	Lab	1876	1905	2003	1930
	Field	2695	2875	3237	2940
	Core	3055	2693	2629	2790
720 day	Lab	1818	1977	1771	1860
	Field	2487	2793	2946	2740
	Core	2856	2678	2087	2540

Table A.14: RCP Test Data (coulombs), Fall Slab, 65% PC/35% S

Age	Sample Type	Sample 1	Sample 2	Sample 3	Average
28 day	Lab	1744	1714	1753	1740
	Field	2992	3203	2618	2940
	Core	1924	1994	2058	1990
56 day	Lab	1342	1321	1199	1290
	Field	1273	1388	1557	1410
	Core	1634	1503	1500	1550
90 day	Lab	1284	1185	1079	1180
	Field	1397	1488	1684	1520
	Core	1643	1668	1697	1670
180 day	Lab	743	810	797	780
	Field	911	911	1037	950
	Core	1064	1019	1025	1040
360 day	Lab	813	761	748	770
	Field	1294	1049	998	1110
	Core	797	744	701	750
720 day	Lab	651	638	664	650
	Field	764	943	1105	940
	Core	578	587	625	600

Table A.15: RCP Test Data (coulombs), Fall Slab, 60% PC/25% S/15% FA

Age	Sample Type	Sample 1	Sample 2	Sample 3	Average
28 day	Lab	2322	2585	2482	2460
	Field	4025	4471	3842	4110
	Core	3725	3724	3679	3710
56 day	Lab	1847	1667	1871	1800
	Field	3817	3425	3240	3490
	Core	3246	3477	3930	3550
90 day	Lab	1726	1455	1493	1560
	Field	2957	3212	2841	3000
	Core	2645	2841	2600	2700
180 day	Lab	990	972	1033	1000
	Field	2305	1858	1996	2050
	Core	1461	1332	1466	1420
360 day	Lab	936	918	925	930
	Field	1881	1885	1997	1920
	Core	1480	1109	1081	1220
720 day	Lab	733	855	838	810
	Field	1395	1419	1361	1390
	Core	980	1141	1047	1060

Table A.16: RCP Test Data (coulombs), Spring Slab, 100% PC

Age	Sample Type	Sample 1	Sample 2	Sample 3	Average
28 day	Lab	2797	2969	-	2880
	Field	3541	4260	-	3900
	Core	2713	2829	2642	2730
56 day	Lab	2065	1985	2067	2040
	Field	2644	2207	2281	2380
	Core	1978	1802	1437	1740
90 day	Lab	1890	1785	1963	1880
	Field	2685	2454	2476	2540
	Core	1980	1893	1678	1850
180 day	Lab	1659	1716	1721	1700
	Field	2584	2529	2563	2560
	Core	1570	1745	1761	1690
360 day	Lab	1607	1472	1320	1470
	Field	2355	2151	2293	2270
	Core	1659	1838	1567	1690
720 day	Lab	1330	1429	1164	1310
	Field	1878	1818	1724	1810
	Core	1018	1966	1515	1500

Table A.17: RCP Test Data (coulombs), Spring Slab, 65% PC/35% S

Age	Sample Type	Sample 1	Sample 2	Sample 3	Average
28 day	Lab	1596	1600	1556	1580
	Field	2677	2744	2648	2690
	Core	2500	2101	2086	2230
56 day	Lab	1029	1078	1034	1050
	Field	1523	1852	1862	1690
	Core	1243	1710	1510	1490
90 day	Lab	1052	1080	1105	1080
	Field	1855	1588	1746	1730
	Core	860	1469	1095	1140
180 day	Lab	919	973	812	900
	Field	1470	1435	1520	1480
	Core	907	1081	1223	1070
360 day	Lab	992	1003	824	940
	Field	1699	1877	1491	1690
	Core	1490	1792	1303	1530
720 day	Lab	650	732	652	680
	Field	1085	1203	1015	1100
	Core	988	1147	1071	1070

Table A.18: RCP Test Data (coulombs), Spring Slab, 60% PC/25% S/15% FA

Age	Sample Type	Sample 1	Sample 2	Sample 3	Average
28 day	Lab	1437	1664	1696	1600
	Field	1712	2229	2101	2010
	Core	2244	1797	1176	1740
56 day	Lab	1194	1243	1074	1170
	Field	2057	1632	1735	1810
	Core	1368	1259	1190	1270
90 day	Lab	1078	1122	1227	1140
	Field	1832	1158	1674	1550
	Core	1234	1077	1249	1190
180 day	Lab	866	843	985	900
	Field	1404	1490	1523	1470
	Core	1014	802	1407	1070
360 day	Lab	790	881	812	830
	Field	1301	1216	1152	1220
	Core	1559	1429	1034	1340
720 day	Lab	645	577	642	620
	Field	886	1044	927	950
	Core	645	666	801	700

Table A.19: Boil Test Data (% voids), Summer Slab, 100% PC

Age	Sample Type	Sample 1	Sample 2	Sample 3	Average
28 day	Lab	12.8%	12.3%	12.4%	12.5%
	Field	14.9%	13.1%	12.8%	13.6%
	Core	12.8%	13.0%	12.3%	12.7%
56 day	Lab	13.1%	12.5%	12.6%	12.7%
	Field	14.3%	13.6%	14.3%	14.1%
	Core	13.4%	12.9%	13.4%	13.3%
90 day	Lab	12.4%	12.0%	12.9%	12.4%
	Field	14.9%	13.7%	14.4%	14.4%
	Core	12.8%	13.0%	13.9%	13.2%
180 day	Lab	12.7%	10.5%	12.0%	11.7%
	Field	13.9%	14.0%	13.7%	13.9%
	Core	11.9%	11.0%	11.6%	11.5%
360 day	Lab	11.6%	11.8%	11.7%	11.7%
	Field	14.4%	14.6%	13.3%	14.1%
	Core	13.5%	14.6%	12.2%	13.4%
720 day	Lab	11.5%	12.3%	11.6%	11.8%
	Field	13.5%	13.8%	13.0%	13.5%
	Core	13.2%	12.8%	12.4%	12.8%

Table A.20: Boil Test Data (% voids), Summer Slab, 65% PC/35% S

Age	Sample Type	Sample 1	Sample 2	Sample 3	Average
28 day	Lab	12.4%	12.1%	12.2%	12.2%
	Field	13.4%	13.4%	12.9%	13.2%
	Core	12.8%	13.0%	14.0%	13.3%
56 day	Lab	12.6%	12.3%	12.1%	12.3%
	Field	14.3%	13.7%	13.8%	13.9%
	Core	15.6%	13.0%	12.9%	13.9%
90 day	Lab	11.8%	11.7%	11.7%	11.8%
	Field	13.7%	12.9%	13.1%	13.2%
	Core	12.9%	13.0%	13.2%	13.0%
180 day	Lab	12.7%	12.7%	11.9%	12.4%
	Field	13.6%	13.7%	13.4%	13.5%
	Core	11.8%	12.3%	12.7%	12.3%
360 day	Lab	11.5%	11.4%	11.3%	11.4%
	Field	12.1%	12.3%	12.3%	12.2%
	Core	12.7%	12.5%	13.6%	13.0%
720 day	Lab	11.6%	11.7%	11.6%	11.6%
	Field	10.7%	10.5%	10.7%	10.6%
	Core	10.1%	9.5%	9.7%	9.8%

Table A.21: Boil Test Data (% voids), Summer Slab, 60% PC/25% S/15% FA

Age	Sample Type	Sample 1	Sample 2	Sample 3	Average
28 day	Lab	13.3%	12.6%	12.7%	12.9%
	Field	14.7%	14.8%	14.2%	14.6%
	Core	13.0%	13.5%	14.1%	13.6%
56 day	Lab	12.8%	13.2%	12.5%	12.8%
	Field	15.5%	14.9%	15.2%	15.2%
	Core	14.7%	13.6%	13.3%	13.9%
90 day	Lab	12.8%	12.7%	12.5%	12.6%
	Field	14.7%	14.3%	14.4%	14.5%
	Core	13.8%	14.1%	12.5%	13.5%
180 day	Lab	13.3%	13.2%	12.6%	13.0%
	Field	14.6%	14.6%	13.4%	14.2%
	Core	12.1%	12.2%	12.1%	12.1%
360 day	Lab	12.6%	12.5%	12.5%	12.5%
	Field	14.4%	13.0%	13.3%	13.6%
	Core	13.6%	13.0%	12.7%	13.1%
720 day	Lab	12.6%	12.9%	12.6%	12.7%
	Field	13.0%	13.2%	12.4%	12.9%
	Core	14.2%	12.9%	13.0%	13.4%

Table A.22: Boil Test Data (% voids), Fall Slab, 100% PC

Age	Sample Type	Sample 1	Sample 2	Sample 3	Average
28 day	Lab	12.5%	12.4%	12.3%	12.4%
	Field	13.5%	13.2%	12.9%	13.2%
	Core	12.5%	12.6%	13.7%	13.0%
56 day	Lab	12.0%	12.0%	11.7%	11.9%
	Field	12.5%	13.1%	13.2%	12.9%
	Core	11.9%	11.9%	12.3%	12.0%
90 day	Lab	12.0%	12.2%	11.7%	11.9%
	Field	12.7%	12.3%	12.8%	12.6%
	Core	12.4%	12.6%	12.7%	12.6%
180 day	Lab	12.4%	11.7%	11.6%	11.9%
	Field	12.0%	12.0%	12.9%	12.3%
	Core	11.8%	11.7%	14.5%	12.7%
360 day	Lab	12.0%	11.9%	11.2%	11.7%
	Field	12.3%	12.1%	11.9%	12.1%
	Core	11.7%	12.0%	11.7%	11.8%
720 day	Lab	11.8%	11.2%	10.7%	11.2%
	Field	12.2%	12.1%	11.9%	12.1%
	Core	13.5%	13.5%	12.8%	13.3%

Table A.23: Boil Test Data (% voids), Fall Slab, 65% PC/35% S

Age	Sample Type	Sample 1	Sample 2	Sample 3	Average
28 day	Lab	12.1%	11.7%	11.7%	11.8%
	Field	13.0%	12.7%	13.4%	13.0%
	Core	12.4%	12.2%	12.4%	12.3%
56 day	Lab	11.6%	11.4%	11.8%	11.6%
	Field	12.8%	13.4%	13.2%	13.1%
	Core	13.1%	12.5%	12.7%	12.8%
90 day	Lab	12.2%	11.5%	12.2%	12.0%
	Field	13.5%	12.1%	12.7%	12.7%
	Core	12.2%	12.6%	12.5%	12.4%
180 day	Lab	12.3%	11.7%	10.9%	11.7%
	Field	13.4%	13.3%	13.7%	13.5%
	Core	13.3%	12.7%	12.8%	12.9%
360 day	Lab	11.4%	12.1%	11.0%	11.5%
	Field	12.7%	12.0%	12.2%	12.3%
	Core	12.0%	12.1%	11.5%	11.9%
720 day	Lab	12.0%	11.1%	11.3%	11.5%
	Field	13.4%	12.0%	12.9%	12.8%
	Core	13.1%	11.6%	12.0%	12.2%

Table A.24: Boil Test Data (% voids), Fall Slab, 60% PC/25% S/15% FA

Age	Sample Type	Sample 1	Sample 2	Sample 3	Average
28 day	Lab	14.7%	14.7%	14.3%	14.6%
	Field	17.7%	17.8%	16.6%	17.3%
	Core	14.7%	15.1%	16.0%	15.3%
56 day	Lab	13.5%	14.6%	13.9%	14.0%
	Field	16.0%	16.0%	15.8%	15.9%
	Core	14.2%	15.1%	14.8%	14.7%
90 day	Lab	14.0%	14.2%	13.9%	14.1%
	Field	16.4%	16.8%	16.8%	16.7%
	Core	15.5%	11.7%	16.2%	14.4%
180 day	Lab	14.0%	13.8%	14.0%	13.9%
	Field	15.7%	15.0%	14.5%	15.1%
	Core	15.5%	15.2%	14.7%	15.1%
360 day	Lab	14.1%	13.7%	14.0%	13.9%
	Field	16.4%	15.9%	15.8%	16.0%
	Core	15.2%	15.6%	14.6%	15.1%
720 day	Lab	13.6%	13.9%	13.7%	13.7%
	Field	15.1%	15.3%	14.8%	15.1%
	Core	15.4%	15.5%	14.8%	15.3%

Table A.25: Boil Test Data (% voids), Spring Slab, 100% PC

Age	Sample Type	Sample 1	Sample 2	Sample 3	Average
28 day	Lab	11.2%	11.0%	11.1%	11.1%
	Field	12.5%	12.7%	11.5%	12.2%
	Core	11.8%	11.7%	11.1%	11.5%
56 day	Lab	10.5%	10.2%	10.2%	10.3%
	Field	10.6%	10.7%	10.8%	10.7%
	Core	10.5%	10.3%	10.4%	10.4%
90 day	Lab	9.7%	10.4%	10.2%	10.1%
	Field	11.2%	11.4%	10.4%	11.0%
	Core	10.2%	10.4%	10.1%	10.2%
180 day	Lab	10.1%	9.7%	10.3%	10.0%
	Field	11.4%	11.2%	10.5%	11.0%
	Core	10.3%	10.1%	10.1%	10.2%
360 day	Lab	10.7%	10.4%	10.6%	10.6%
	Field	11.8%	11.7%	11.3%	11.6%
	Core	11.0%	10.6%	10.7%	10.8%
720 day	Lab	10.0%	10.0%	9.3%	9.8%
	Field	10.4%	10.2%	9.9%	10.2%
	Core	9.8%	10.0%	9.7%	9.8%

Table A.26: Boil Test Data (% voids), Spring Slab, 65% PC/35% S

Age	Sample Type	Sample 1	Sample 2	Sample 3	Average
28 day	Lab	12.0%	11.3%	11.4%	11.6%
	Field	13.4%	13.6%	12.9%	13.3%
	Core	12.6%	12.8%	12.9%	12.8%
56 day	Lab	11.4%	11.6%	11.8%	11.6%
	Field	13.2%	12.8%	13.7%	13.2%
	Core	13.2%	13.5%	12.4%	13.0%
90 day	Lab	11.1%	10.8%	11.0%	11.0%
	Field	13.3%	12.0%	12.4%	12.6%
	Core	12.2%	13.5%	13.6%	13.1%
180 day	Lab	11.8%	11.7%	11.4%	11.6%
	Field	12.8%	13.4%	12.2%	12.8%
	Core	12.7%	12.2%	11.7%	12.2%
360 day	Lab	11.3%	11.9%	11.3%	11.5%
	Field	13.0%	12.9%	13.8%	13.2%
	Core	13.6%	12.9%	12.7%	13.1%
720 day	Lab	10.4%	10.7%	10.3%	10.5%
	Field	11.6%	11.7%	12.2%	11.8%
	Core	12.0%	12.1%	13.4%	12.5%

Table A.27: Boil Test Data (% voids), Spring Slab, 60% PC/25% S/15% FA

Age	**Sample Type**	**Sample**			**Average**
		1	**2**	**3**	
28 day	Lab	11.3%	11.5%	11.5%	11.4%
	Field	13.0%	12.2%	12.9%	12.7%
	Core	12.0%	11.7%	12.1%	11.9%
56 day	Lab	11.2%	11.8%	11.5%	11.5%
	Field	12.8%	12.6%	12.4%	12.6%
	Core	12.3%	11.6%	11.9%	11.9%
90 day	Lab	11.2%	11.2%	11.9%	11.5%
	Field	13.0%	13.2%	13.5%	13.2%
	Core	12.0%	13.4%	12.5%	12.6%
180 day	Lab	10.2%	10.3%	11.0%	10.5%
	Field	12.4%	12.7%	12.4%	12.5%
	Core	12.6%	10.6%	11.8%	11.7%
360 day	Lab	11.8%	11.9%	11.6%	11.7%
	Field	13.0%	13.1%	13.7%	13.3%
	Core	13.0%	13.7%	11.7%	12.8%
720 day	Lab	10.4%	10.7%	10.7%	10.6%
	Field	12.7%	13.4%	13.0%	13.0%
	Core	11.9%	11.5%	11.3%	11.6%