EFFECT OF CURING CONDITIONS ON SURFACE RESISTIVITY IN HIGH PERFORMACE CONCRETE

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ABSTRACT OF THE THESIS

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The testing presently in practice for assessing the resistance of concrete to penetration of chloride ions is ASTM C1202 or Rapid Chloride permeability test (RCPT) titled “Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration”. This test is considered to be prolonged, laborious, and of relatively high variability, due to certain parameters such as the test being user sensitive. As an alternative to the RCPT, the Surface Resistivity (SR) Test as presented in AASHTO TP 95-11 titled “Surface Resistivity Indication of Concrete’s Ability to Resist Chloride Ion Penetration” was investigated by correlating the results of the two tests. SRT is considered to be cost and time effective, as well as of relatively lower variability. Curing standards have been criticized in the industry due to their focus on strength properties, leaving out the effect of curing on durability properties of concrete. The research reported herein is focused on determining a correlation between RCP and SR test measurements and investigate the effect of different curing methods including accelerated curing on the correlation in High Performance Concrete (HPC). This research also investigates the effect of specific cementitious materials and chemical admixtures of surface resistivity and rapid chloride permeability results in three different curing methods. The HPC samples tested and included in this study were collected from various NJDOT and NJTA field locations in New Jersey and some cylinders were reproduced in the laboratory based on field High Performance Concrete mixture design.

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CHAPTER I

1 INTRODUCTION

1.1 PROBLEM STATEMENT

Concrete with its strength, durability and economical advantage has become the most used man-made construction material. The evolution of bridge construction shifted from large compression-only structures towards less space consuming flatter structures withstanding larger tension; increasing the use of steel reinforcement. Although there are many advantages of using steel-reinforced concrete such as speed of construction, substantial economy, fire resistance, flexibility in design and minimum maintenance. The fact that steel is susceptible to corrosion remains its main disadvantage. Reinforcing steel in concrete ideally does not corrode since protection is provided by the formation of a passive oxide coating on the surface of the steel due to the initial corrosion reaction. The process of cement hydration in freshly poured concrete develops a high alkalinity, which in the presence of oxygen stabilizes the coating on the surface of the reinforcing steel, ensuring continued protection while alkalinity is retained. However, crack formation in concrete remains unavoidable due to many factors such as shrinkage reactions of setting concrete and tensile stresses occurring in the structure. Crack formation reduces the durability of the concrete as it increases the concrete’s permeability which allows for carbonation and aggressive elements such as chloride to corrode the reinforcing steel. On top of that, the ingress of the chloride ions into the concrete results in further cracking due to corrosion induced cracking.

Due to the grave effects of corrosion on structural integrity, chloride ion penetration is a vital measure of durability. The testing presently in practice for assessing the resistance of concrete to penetration of chloride ions is ASTM C1202 or Rapid Chloride permeability test (RCPT) titled “Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration”. This test is considered to be prolonged, laborious, and of relatively high variability, due to certain parameters such as the test being user sensitive. As an alternative to the RCPT, the Surface Resistivity (SR) Test as presented in AASHTO TP 95-11 titled “Surface Resistivity Indication of Concrete’s Ability to Resist Chloride Ion Penetration” was investigated by correlating the results of the two tests. SRT is considered to be cost and time effective, as well as of relatively lower variability.

There are various types of curing for different types of construction under different weather conditions .there are various types of curing for different types of construction under different weather conditions .Curing regimes play a critical role in obtaining desired concrete strength and durability characteristics. It is therefore important to identify the effect of curing regimes on concrete strength and durability of concrete.

The research reported herein is focused on determining a correlation between RCP and SR test measurements and investigate the effect of different curing methods including accelerated curing on the correlation. The cylinders tested were collected from various NJDOT and NJTA field locations in New Jersey and some cylinders were reproduced in the laboratory based on HPC field mix designs.

1.2 RESEARCH OBJECTIVES AND SCOPE

When compared with RCPT, the SRT is a relatively recent test that has been recently adopted in the specifications, and thus there is limited literature investigating the factors that affect the SR of concrete. Studies have shown that the factors affecting RCPT readings include: mixture proportions, time and curing conditions. In this study, different mixes' penetrability has been measured with each of these tests under five different curing methods including: Moist Curing, Water Bath, Lime Bath and accelerated curing with and without lime.

The objectives of this research project are to investigate the correlation of RCP and SR results and how the curing methods affect the results and the correlation. To achieve this objective, concrete samples were collected from actual bridge deck pours across the state of New Jersey and tested using both the RCPT and the SRT to evaluate the correlation between the two measurements as well as to study the effect of curing methods on the results and the correlation.

1.3 THESIS ORGANIZATION

This thesis consists of five chapters as the following:

Chapter I serves as an introduction consisting of the problem statement, research objective and scope and thesis organization.

Chapter II covers the general background and literature review on High Performance concrete, mechanisms of chloride ion penetration, Rapid chloride permeability test , surface resistivity test and curing regimes

Chapter III covers the experimental program including the material properties and supplies as well as the mixing and testing procedures.

Chapter IV covers the results of the tests, including the effect of curing on rapid chloride permeability, surface resistivity and strength, as well as RCP and SR correlation

Chapter V covers the conclusions, recommendations and possible scope for future research.

CHAPTER II

2 LITERATURE REVIEW

2.1 INTRODUCTION

High Performance Concrete (HPC) has gained popularity over the years all around the world and especially in highway bridges due to its strength and durability characteristics that exceed traditional concrete. The Federal Highway Administration (FHWA) implements four durability characteristics and four structural characteristics to define HPC and evaluate performance. The durability performance characteristics include Chloride Penetration based on ASTM C 1202 and AASHTO T 277 standard tests. (Russell, et al, 2006) Penetration of chloride ions into the concrete results in rapid deterioration of reinforced concrete structures due to reinforcement corrosion; the repair cost of which is estimated at over $20 billion annually in the US (Gannon & Cady, 1992). Corrosion is considered to be the single most important cause of damage to concrete bridges. The low permeability of HPC has increased its demand the construction industry. The testing presently in practice for assessing the resistance of concrete to penetration of chloride ions is ASTM C1202 or Rapid Chloride permeability test (RCPT) titled “Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration”. This test is considered to be prolonged, laborious, and of relatively high variability, due to certain parameters such as the test being user sensitive. As an alternative to the RCPT, the Surface Resistivity (SR) Test as presented in AASHTO TP 95-11 titled "Surface Resistivity Indication of Concrete's Ability to Resist Chloride Ion Penetration" was investigated by correlating the results of the two tests. SRT is considered to be cost and time effective, as well as of relatively lower variability. (Ramezanianpour, et al, 2010)

2.2 MECHANISMS OF CHLORIDE ION PENETRATION

The four major processes of concrete penetration by liquids containing chloride ions are hydrostatic pressure, evaporative transport, diffusion and capillarity. Hydrostatic pressure is a factor of height, density and gravity. In this process the liquid at rest on the surface penetrates the concrete due to a continual hydraulic head between the concrete's interior and exterior. Shrinkage and creep due to thermal expansion and contraction would not only cause crack formation but also would assist liquids in its tendency to flow into capillaries, or voids, in the concrete. Such a penetration, referred to as capillarity, would accumulate chloride ions in concrete voids over time. Of these three major processes, diffusion presents the most prominent concern on concrete penetration in bridge decks. (Hamilton III & Boyd, 2007)

Diffusion, simply defined in this case, is the flow of molecules from areas of higher concentration to areas of lower concentration; or down a concentration gradient. During winter and snow storms, a very common practice is spreading deicing salts, sodium chloride, on bridge decks and roads to melt ice in a more efficient manner and maintain traffic flow. Although there are many environmental and safety advantages of deicing salts, the high concentration of chloride on bridge deck surfaces develop a concentration gradient and thus diffuse into the concrete. (Stanish, et al, 2000)

Evaporative transport is the process of which vapor is conducted from areas of higher moisture to areas of lower moisture.In an exposed area, the evaporation of water leaves behind , in this case, chloride ions in concrete voids. (Tuutti, 1982)

The process of cement hydration in freshly poured concrete develops a high alkalinity, which in the presence of oxygen stabilizes the coating on the surface of the reinforcing steel, ensuring continued protection while alkalinity is retained. However, crack formation reduces the durability of the concrete as it increases the concrete’s permeability which allows for carbonation and aggressive elements such as chloride to corrode the reinforcing steel. On top of that, the ingress of the chloride ions into the concrete results in further cracking due to corrosion induced cracking. (Wee, Suryavanshi,, & Tin, 2000)

2.3 HIGH PERFORMANCE CONCRETE

Many solutions have introduced in the industry to combat the deteriorating effects of chloride ion penetration in concrete, however, following the philosophy that prevention is better than cure, High-performance concrete (HPC) is now widely used on bridge decks and many other applications to reduce concrete permeability.

Conventional concrete consists of certain proportions of water, binder, aggregate and occasionally chemical admixtures. Unlike conventional concrete, HPC include materials other than cement to achieve certain requirements, such as flyash, slag and microsilica fume while maintaining a water cement ratio of about 0.20-0.45. (Meeks &

Carino, 1999) Depending on the requirement, certain proportions of these cementitious materials are combined with Portland cement. Plasticizers and admixtures, such as High-Range Water Reducer (HRWR) and Accelerator or Retarder, are also added to increase required workability.

HPC is designed to meet specific performance and durability specifications that cannot be attained solely through using conventional materials or mixing, pouring, and curing techniques. Strength criteria used to evaluate high performance concrete include: Compressive strength, Modulus of Elasticity, Shrinkage and Creep. As for durability, criteria include: Freeze-Thaw, Scaling, Abrasion and Chloride Permeability. (Russell, et al, 2006) The American Concrete Institute (ACI) defines HPC as “concrete meeting special combinations of performance and uniformity requirements that cannot always be achieved routinely using conventional constituents and normal mixing, placing, and curing practices.” (ACI, 2014) There are many definitions to HPC, referred to as classifications, each of which depends on the performance requirement. Performance requirements encompass not only strength properties but rather many factors including resistance to environmental conditions and durability.

2.3.1 Characteristics of High Performance Concrete

The Federal Highway Administration (FHWA) implements four durability characteristics and four structural characteristics to define HPC and evaluate performance grades. HPC is designed to meet specific performance and durability specifications that cannot be attained solely through using conventional materials or mixing, pouring, and curing techniques. Strength criteria used to evaluate high performance concrete include: Compressive strength, Modulus of Elasticity, Shrinkage and

Creep. As for durability, criteria include: Freeze-Thaw, Scaling, Abrasion and Chloride Permeability. Table 2.1 lists the characteristics of HPC.

Table 2.1 Characteristics of High Performance Concrete (Meeks & Carino, 1999)

Characteristics of High Performance Concrete	
High-Strength	Resistance to chemical attack
High-Early Strength	High resistance to frost
High modulus of elasticity	High resistance deicer damage
Self-Consolidating	Toughness and impact resistance
High-Durability	Volume stability
Reactive Powder	Ease of placement
long life in severe environments	Compaction without segregation
Low permeability and diffusion	Inhibition of bacterial and mold growth

2.3.2 HPC Test Methods

The FHWA utilizes accepted standard tests by AASHTO and ASTM for each performance characteristic to determine HPC grade. Standard test for some performance characteristics are outline in Table 2.2.

Table 2.2 HPC Performance Characteristics Standard Test Methods (Russell, et al, 2006)

Characteristic	Description	Standard Test
Freeze-Thaw Durability	Relative dynamic modulus of elasticity after 300 cycles	AASHTOT 161 ASTM C 666 Proc. A
Scaling Resistance	Visual rating of the surface after 50 cycles	ASTM C 672
Abrasion Resistance	Avg. depth of wear in mm	ASTM C 944
Chloride Penetration	Coulombs	AASHTO T 277 ASTM C 1202
Strength	Compressive strength	AASHTO T 2 ASTM C 39
Elasticity	Modulus of elasticity	ASTM C 469
Shrinkage	Microstrain	ASTM C 157
Creep	Microstrain/pressure unit	ASTM C 512

2.3.3 HPC Materials

The low water-cement ratio and high heat of hydration in HPC assists in preventing segregation and bleeding. This results in faster drying at the surface than the interior leading to plastic shrinkage cracking. (Coulombe & Ouellet , 1995) Although suitable curing in each case may assist in eliminating such issues, the use of cementitious materials and chemical admixtures are effective methods to achieve desirable properties and avoid undesirable factors. Cementitious materials typically enhance the concrete by improving pozzolanic and micro filler effects. (Ajay, et al, 2012) This section outlines materials used in manufacturing HPC concrete which are not conventionally found in traditional concrete.

2.3.3.1 Chemical Admixture

In the concrete industry, chemical admixtures are used to address many issues such as bleeding, segregation setting time and shrinkage.

2.3.3.1.1 Air entraining admixtures

Air entraining admixtures (AEA) cause microscopic stable bubbles of air to form evenly throughout the concrete mix to absorb concrete expansion. AEA are conventionally added to improve workability in concretes susceptible to freeze-thaw or poured in environmental conditions where temperature instability may cause undesirable factors in the concrete. AEA is introduced during mixing and thus it is necessary to test on the field for site pours and not at the plant since mixing takes place in the concrete trucks as well. AEA are also used to reduce bleeding and segregation which leads to increasing service life and enhancing durability. (Du & Folliard, 2005)

2.3.3.1.2 Water Reducers

Water Reducers (WR) are used to reduce the amount of water used by around ten percent. High Range Water Reducer (HRWR) Superplasticizers are used to further reduce amount of water reduced by up to thirty percent. Since it affects fresh concrete properties, its effects are tested for by one the fresh concrete properties tests, known as the slump test. Utilizing certain chemicals, such as hydrocarboxylic acid, WR may be designed and applied to accelerate or retard the concrete setting time as desirable. For accelerators, the industry has moved towards non-calcium chloride chemicals to avoid negatively impacting fresh concrete properties. Desirable effects of WR include less bleeding and segregation, early strength enhancement, increase of slump, reduced permeability, increased workability and durability. The use of WR is very beneficial in HPC where a lower water- cementitious ratio is required. (Neville, 1995)

2.3.3.2 Fly ash

The use of fly ash as a pozzolan in the concrete industry has been consistently increasing over the past few decades. Fly Ash is a by-product of the coal burning process generally at electric power generation plants and thus it presents an economical advantage over Portland cement. It is used as a supplementary cementitious material to replace a portion of the Portland cement used in concrete mixtures. As it is exposed to moisture, it forms cementitious compounds adding density and strength to the concrete. Having a finer particles than cement, fly ash increases workability, pump ability and alkali and sulfate aggregate resistance. By reducing the amount of water needed, fly ash is also credited for reducing permeability, bleeding and segregation. (Thomas, 2007)

2.3.3.3 Ground Granulated Blast-Furnace Slag

Another pozzolanic cementitious material used in HPC is ground granulated blast furnace slag (GGBFS) or slag. Slag is obtained from blast-furnaces as a by-product of iron manufacturing. It is also used as a supplementary cementitious material to replace a portion of the Portland cement used in concrete mixtures. Like fly ash, slag also presents and economical advantage over Portland cement. Depending on percentage of substituted cement with slag and slag grade desirable benefits of slag include reduction in water demand, extension of setting time, increased workability and reduced permeability. Slag concrete mixes demonstrate higher resistance to chemical attack than traditional concrete. (Osborne, 1999)

2.3.3.4 Silica fume

Microsilica, or silica fume, is another pozzolanic cementitious material used in HPC. Silica fume is an ultrafine powder obtained from electric furnaces as a byproduct silicon and ferrosilicon alloy production. (Ajay, et al, 2012) Although with the introduction of silica fume into the mix , water demand is slightly increased , concretes with portions of cement substituted for with silica fume tend to demonstrate higher compressive and bond strength as well as higher resistance to chemical attack and deterioration. Conventionally, admixtures, such as AEA and HRWR, are added as needed when silica fume is introduced to maintain required air content and compensate for increased water demand. (Carette & Malhotra, 1983)

2.4 CURING REGIMES

The American Concrete Institute (ACI) definition of curing is “action taken to maintain moisture and temperature conditions in a freshly placed cementitious mixture to allow hydraulic cement hydration and (if applicable) pozzolanic reactions to occur so that the potential properties of the mixture may develop”. (ACI, 2013) There are various types of curing for different types of construction under different weather conditions. Curing regimes can be compiled into two categories: curing with water and curing preventing moisture loss. Excess water in conventional concrete with water-cementitious materials ratio greater than about 0.45, would lead to the observance of very close results in both categories of curing. On the other hand due to the lower water-cementitious materials ratios in high-performance concrete, studies have shown that favorable results are observed with water curing. Curing standards have been criticized in the industry due to their focus on strength properties, leaving out the effect of curing on durability properties of concrete. (Carino & Meeks, 2001)

2.5 SALT PONDING TEST

The Salt Ponding test, standardized in AASHTO T 259 and ASTM C1543, has been widely used and adopted for determining concrete resistance to chloride ion penetration by the simulation of such penetration into concrete bridge decks. The test specimens consist of three concrete slabs with a 3-inch thickness. A 12-inch square plastic dike is assembled around the top perimeter of the slab to hold the 3% Sodium Chloride (NaCl) ponding solution while the bottom perimeter remains exposed. During the conditioning phase, the specimens are moist cured for a certain period of time and then stored in a dry 50 percent relative humidity environment. AASHTO T 259 specifies moist curing for 14 days and then drying for 28 days, while ASTM C1543 specifies moist curing until 14 days or a specified compressive strength is reached. The ponded slabs are stored in a 50 percent relative humidity environment. To prevent water evaporation and to maintain a constant concentration of NaCl in the solution, a cover is placed over the plastic dike. AASHTO T 259 specifies a 90 day ponding period after which chloride ion content is determined from 0.5-inch thick specimens according to AASHTO T 260. ASTM C1543 specifies initial sampling of 0.5-inch thick specimens at 90 days ,according to ASTM C1152, and later sampling at different durations (6 and 12 months) for more accurate evaluation of low-permeability concretes.

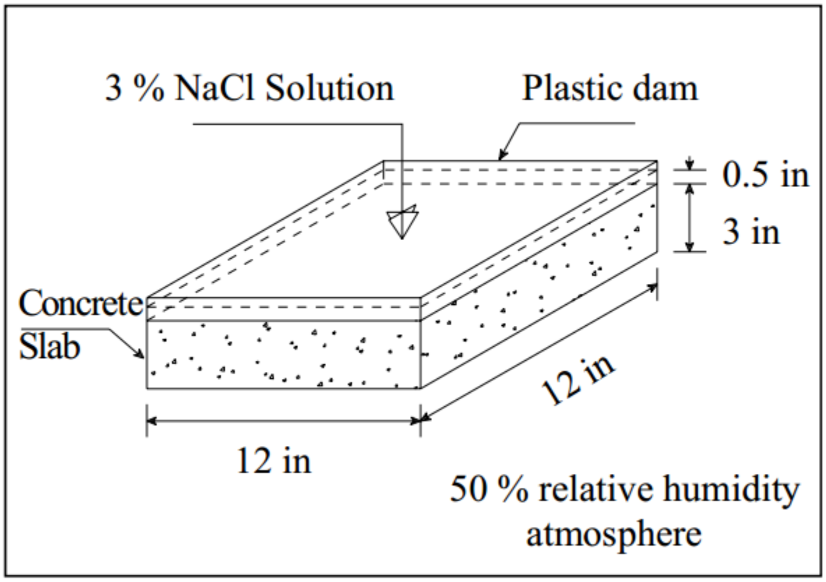

Figure 2.1 Salt Ponding Test (Stanish, Hooton, & Thomas, 2000)

The ponding test is criticized for its lack of emphasis on the importance of mechanisms of chloride transportation into the concrete. The test setup and conditioning phase, result in chloride ion penetration through mechanisms besides diffusion such as sorption and wicking. The sorption effect takes place after the 28 day drying period after which the salt solution is poured in the dike on the specimens. As for wicking, it is due to the difference in relative humidity between the diked and exposed areas resulting in moisture transmission and further chloride ion penetration. (Stanish, Hooton, & Thomas, 2000) The amount and speed of chloride ion penetration depends on their mechanisms of transportation which in turn in influenced by many factors such as chemical concentration and environmental conditions.

2.6 RAPID CHLORIDE PERMEABILITY (RCP) TEST

The testing presently in practice for assessing the resistance of concrete to penetration of chloride ions is ASTM C1202 (AASHTO T277) or Rapid Chloride

Permeability (RCP) test titled “Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration”. (ASTM, 2012) The RCP test measure concrete electrical conductivity which provides an indication of chloride ion penetration in terms of charged passed (coulombs).

Concrete’s ability to resist chloride penetration is a determining factor when evaluating performance and durability. This characteristic of concrete is measured and determined by a standard test method for electrical indication of concrete’s ability to resist chloride ion penetration known as the rapid chloride permeability test (RCPT). This test was initially developed by the Portland Cement Association, for a research program sponsored by the Federal Highway Administration (FHWA). The test methodology has been revised and adopted by the construction industry and many agencies and organizations such as the American Association of State Highway and Transportation Officials (AASHTO – T277) and the American Society for Testing and Materials (ASTM- C1202). (GRACE, 2006) The RCP test measures concrete electrical conductivity which provides an indication of chloride ion penetration in terms of charge passed (coulombs); through monitoring an electrical current passed through a concrete specimen over a period of 6 hours. (Stanish, Hooton, & Thomas, 2000) Before conducting this test, there are certain conditioning procedures that would require up to 20 hours for completion. A direct current induced by a 60 V potential difference, causes the transportation of ions between two reservoirs in the cell block containing 3.0 % Sodium Chloride (NaCl) and 0.3 N Sodium Hydroxide (NaOH) solutions.

The electric charges effective path length exceeds the thickness of the concrete specimens due to nonconductive and obstructing particles in the concrete referred to as concrete tortuosity. Electrical conductance is determined quantitatively by the measurement of passing charges in coulombs over the test duration. The total charges passed give an indication of the specimen's resistance to chloride ion penetration. (Stanish, Hooton, & Thomas, 2000)The ranges set for RCPT readings to rate chloride ion penetrability are listed in Table 2.3 below. Due to the effect of testing age and curing conditions on chloride ion penetrability, standards, such as ASTM C1202, identify procedures and testing age for the applicability of the rating ranges provided.

Table 2.3 Chloride Ion Penetrability Based on Charge Passed (ASTM C1202)

Charge Passed (coulombs)	**Chloride Ion Penetrability**
> 4,000	High
2,000 - 4,000	Moderate
1,000 - 2,000	Low
100 - 1,000	Very Low
< 100	Negligible

2.6.1.1 RCP Test Criticisms

Although the RCP test is currently in practice and widely accepted by many departments of transportation in the US, such as NJDOT, there has been much controversy against its effectiveness. (Wee, et al, 2000)

The RCP test provides means, through electric indication, to estimate concrete's resistance to chloride ion penetration. In some cases, and for simplicity, the RCP test readings are accepted as indicators of permeability. However, in this context permeability refers to the penetration of water carrying ions into the concrete and not solely chloride ion penetration. Many studies indicate that while the RCP test has correlated well with the conventional ponding test, ASTM C1543, in conventional concrete, this coloration does not hold when with concretes containing pozzolans and chemical admixtures. (Wee, et al, 2000)

Researchers agree that the introduction of pozzolans and chemical admixtures into the concrete, such as in HPC, the chemistry of the pore solution is altered. (Shi, et al, 1998). This alteration in the pore structure chemistry will impact RCP test results, typically with lower reading, and thus the effectiveness of this test as an indicator of chloride ion penetration. (Shi & Caijun, 2004). Researchers also argue that since the desirable effects of added pozzolans to enhance the concrete may not have been achieved yet during the first fifty six days due to their reaction time and behavior, although it has been proven and accepted that pozzolan containing concretes have lower permeability, the low RCP test reading at that time do not reflect actual chloride ion penetration. (Riding, et al, 2008)

Another criticism of the RCP test is that the current applied through the test cell blocks leads to an increase of specimen temperature which would in turn lead to an increase in RCP test reading. (Riding, et al, 2008).

2.7 SURFACE RESISTIVITY (SR) TEST

Concrete resistivity is considered an effective measure in identifying the risk of reinforcement corrosion. Over the past few decades as the methods used to determine concrete resistivity developed, the popularity of this nondestructive cost saving testing increased. (Millard, et al , 1989)

Before discussing the Surface Resistivity Test (SRT), it is important to make the distinction between resistance and resistivity. Resistance (*R*) the obstruction of electric current (*I*) passage by the conductor, in this context concrete, and is defined with the equation:

$$R\text{(ohms)}=VL$$

where V is voltage and L is current.

As for resistivity (ρ) it is a property of the material and defined with the equation:

$$\rho(\text{ohms} - \text{length}) = \frac{RA}{L}$$

where A is cross-sectional area and L is element length.

The current testing method in practice for surface resistivity involves the use of a light weight hand held device, referred to as a resistivity meter, which measures surface resistivity through four probes, known as Wenner probe, that are pushed against the concrete surface. One of the most recent and simplistic device in the industry is the Resipod Resistivity Meter manufactured by Proceq.

The four probes of the resistivity meter are equally spaced at 50 mm, almost 2 inch, of which a steady current is impressed through the two outer pins, and the current difference is measured by the two inner pins; as illustrated in Figure 2.2.

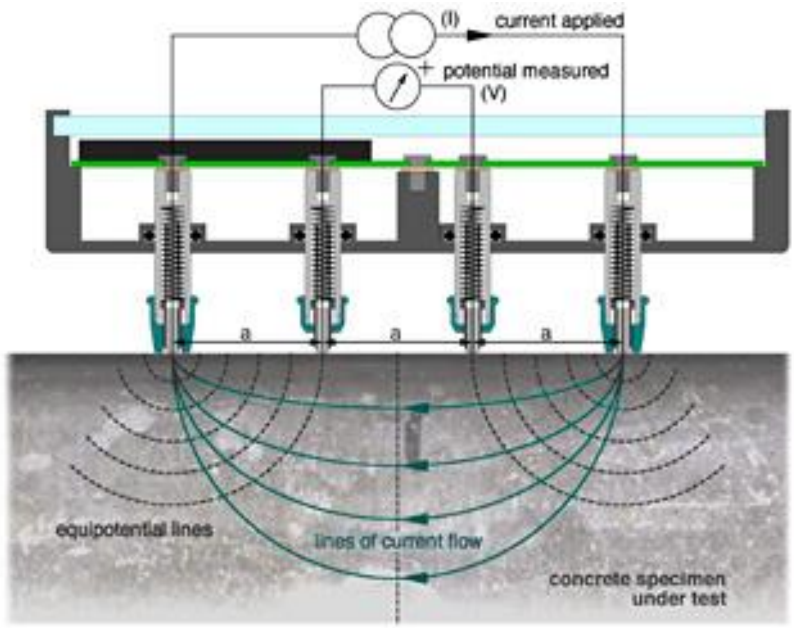

Figure 2.2 Four -probe Resistivity Meter (Humboldt Mfg. Co, 2014)

The surface resistivity limits for chloride ion penetrability indication as specified in AASHTO Designation: TP 95-11 are listed in Table 2.4.

Table 2.4 Surface Resistivity Limits (AASHTO, 2012)

Chloride Ion Penetrability	**Surface Resistivity Test**	
	100-mm X 200-mm (4 in. X 8 in.) Cylinder (KOhm-cm) a = 1.5	**150-mm X 300-mm (6 in. X 12 in.) Cylinder (KOhm-cm) a = 1.5**
High	< 12	< 9.5
Moderate	12 – 21	9.5 – 16.5
Low	21 – 37	16.5 – 29
Very Low	37 – 254	29 – 199
Negligible	> 254	> 199

2.7.1.1 Surface Resistivity (SR) Test Advantages and Criticism

Compared to the RCP test, the SR test presents many advantages that make it a rather attractive alternative. Being a non-destructive test, the SR test is considered to be a sustainable approach towards determining chloride ion penetrability due since is decreases the consumption of resources and raw materials. With the implementation of the SR test, a significantly fewer number of samples would have to be collected by the quality control professionals. Moreover, the consistency of the SR testing is a major advantage over the RCP test. Utilizing this non-destructive test, would allow for the same sample to be used for the compression test as well as the SR test at various agers. With this approach the same cylindrical specimens are used to determine the strength and durability characteristics of the concrete under study. Furthermore, by implementing the SR test there would be substantial cost savings in terms of time and technician labor cost when considering the time it takes to conduct the SR test, approximately 10 minutes, versus the time it takes to complete the RCP test, approximately 24 hours. Cost saving are also present in equipment costs. The resistivity meter cost around $2500 while the entire RCP test set-up including concrete saw costs around $18,000. (Nassif & Na, 2013) Several state agencies across the United States, such as Louisiana Department of Transportation and Development (LADOTD), have adopted the SR test as an alternative to the RCP test. According to Louisiana Transportation Research Center (LTRC) report sponsored by LADOTD, the estimated combined savings the first year of implementation is about $1.6 million. (Rupnow & Icenogle, 2011)

Criticism of the Surface Resistivity test has been with regards to the proper implementation of the testing procedure and field applications. Authors have observed that the presence of steel reinforcements (Garzon, et al, 2014) and cracks (Chen, et al, 2014) alter the surface resistivity readings and investigated the appropriate adjustments for certain cover thicknesses. (Taillet, et al , 2013) However, with laboratory applications and testing of concrete cylinders which do not have reinforcement embedded, such concerns do not apply. Another influencing factor is the non-homogeneity of concrete. The various constituents in the concrete affect the resistivity. (Lataste, 2010) That's why it is necessary to take the measurement at different locations of the cylinder for more uniform and useable readings .Proper implementation of the testing procedure as specified in the standards and by the manufacturer, such as frequent dampening of probes and ensuring contact of all four probes with concrete surface, is absolutely necessary to minimize the user sensitivity drawbacks. With SR testing, there is more control and adjustments are very easy to make. Such drawbacks can be easily avoided.

CHAPTER III

3 EXPERIMENTAL SETUP

3.1 INTRODUCTION

The purpose of this chapter is to describe the procedures used for mixing laboratory mixtures, collecting and transporting field mixes, curing and testing the concrete samples. Tests will include those done on fresh concrete, including Slump, Unit weight and Air Content as well as those performed on hardened concrete, including Compressive Strength, Rapid Chloride Permeability test, and Surface Resistivity test. For laboratory mixtures, fine and coarse aggregate moisture content is determined ensure uniformity between batches. Testing and curing are done according to ASTM and/or AASHTO specifications where applicable. Field samples are provided by the RIME group from NJDOT and NJTPA sponsored projects. A total of sixteen mixtures, six laboratory mixtures and ten field mixtures, are used throughout this study. Curing regimes include moist curing room (CR), water bath (WB), accelerated (hot) water bath (HWB), lime bath (LB) and accelerated (hot) lime bath (HLB).

3.2 SPECIMEN PREPARATION

3.2.1 LABORATORY MIXING AND SAMPLING

Mixing and casting of samples is based on ASTM C192 using a 6 cubic foot capacity portable electric mixer shown below in Figure 3.1.

Figure 3.1 Electric Portable Mixer

3.2.2 Mixing

All material to be used are batched in five gallon buckets and placed within a short distance from the mixer to facilitate the mixing process. Carefully measure proportions of certain admixtures, such as high-range water reducer, is poured into the mixing water bucket and stirred. However other admixtures, retarder and superplasticizer, are introduced into the mix at a later stage to avoid intermixing. Mixing water is split into two buckets, one-third and two-thirds. For practicality and safety the mixer is stopped whenever water, cementitious materials, sand or aggregate are added. The mixer is first rinsed with water and buttered with a mixture of cement, sand and water. Coarse aggregate and the two-third mixing water are then added. After starting the mixer for a few revolutions, fine aggregate is then added. After around one minute, the mixer is stopped again and the remaining mixing water along with all the cementitious materials such as, Fly Ash, Silica Fume or Slag, are added to the mixer. At this point all materials are added to the mixer, and allowed to mix uninterruptedly for three minutes followed by three minutes of rest during which the inside of the mixer can be visually inspected to insure uniformity of mixing. The mixer is then turned on again for two minutes of final mixing. Starting with the slump test, fresh concrete properties tests are performed at this point. If required slump is not met, super plasticizer proportions may be adjusted.

3.2.3 Slump Test

Slump test was performed in accordance to ASTM C134. The test is conducted out using a slump cone mold. First the non-absorbent base plate and the interior of the cone are dampened. The base of the cone, or the end with the larger opening, is then placed on the base plate and fresh concrete is scooped into the mold at three stages each time filling one-third of the mold and immediately followed by uniform rodding with twenty five even strokes. The top of the cone is then leveled and excess concrete is disposed from around the mold base. The mold is then vertically removed carefully and immediately placed beside the slumped concrete. Finally the rod is placed horizontally across the mold and the slump is measured. Slump test set up is demonstrated in Figure 3.2 below.

Figure 3.2 ASTM C134 Slump Test Setup

3.2.4 Pressure Air Content Test

Figure 3.3 ASTM C231 Type B Pressure Air Meter

The next fresh concrete properties test, after meeting required slump, is the ASTM C231 Type B Pressure Air Meter test, shown in Figure 3.3, to determine the air content of the concrete mixtures. This test must be conducted carefully with and the meter must be calibrated correctly for accurate readings.

After the container is washed, it is placed on a flat surface fresh concrete is scooped in at three stages each time filling one-third of the container and immediately followed by uniform rodding with twenty five even strokes and tapped on the sides with a rubber mallet fifteen times to release entrapped air bubbles. Once the container is filled, the top is then leveled and excess concrete is disposed. Before assembling the apparatus the upper flanges are cleaned with a sponge to achieve an airtight connected. Using a squirt bottle water is released into one petcock valve until it flows out through the other. This process is repeated to the other petcock valve and then they are both shut simultanously.in the meantime the container is tapped with the rubber mallet as required.

The air pump is then applied until the pressure gauge needle rests at zero percent. Obtaining zero percent reading with require tapping the gauge however improper calibration or fitting might cause the needle to fluctuate away. Air is then released by opening the main air valve and the needle will move towards the air content reading.

3.2.5 Sampling

Sampling of fresh concrete is conducted in accordance with ASTM C172. Fresh concrete is scooped into four by eight inch plastic cylindrical molds, greased with sampling oil ,at two stages ,each time consolidating using through rodding for twenty five times for each half of the cylinder and then tapping fifteen times. Figure 3.4 demonstrates the molds used for sampling.

Figure 3.4 Molds Prepared for Sampling

3.2.6 Field Sampling

Field samples were collected from concrete bridge deck pours across the state of New Jersey by the Rutgers Infrastructure Monitoring and Evaluation (RIME) Group for NJDOT and NJTA sponsored projects. Depending on the study, a sufficient amount of HPC samples were collected from various locations and taken back to the Rutgers Civil Engineering Laboratory for curing and testing. For field samples ASTM C31 was followed as much as permissible , however for safety reasons and due to construction site regulations some samples had to be transported earlier that the specified time. To compensate, the samples were transported in large cooling boxes and placed in a manner to minimize the effect of vibrations. Figure 3.5 (a) and (b) illustrates the field sampling set up in two different locations.

(a) (b)

Figure 3.5 (a) Field Sampling Setup (NJTA interchange 7A) (b) Field Sampling Setup (El Sol Contracting yard, Jersey City)

During field sampling, slump and air pressure tests are performed by the quality control professionals and the reading are recorded as illustrated in Figure 3.6. Sampling by the RIME group is only conducted after the batch is approved by the quality control professionals. In the batch did not meet requirements, the concrete truck is rejected and leaves the site without pouring.

Figure 3.6 Quality Control Professionals Transporting Fresh Concrete for Slump and Air Pressure Testing (NJTP interchange 7A)

On the site, concrete is poured into a wheel barrel which is then transported to the set up location within a very close radius as shown in Figure 3.6. Fresh concrete is scooped into four by eight inch plastic cylindrical molds, greased with sampling oil ,at two stages ,each time rodding for twenty five times for each half of the cylinder and then tapping fifteen times as illustrated in Figure 3.7.

Figure 3.7 Rodding Fresh Concrete in Molds (NJTP interchange 7A) (b)

The top of the molds then leveled and excess concrete is disposed. At this point the molds are covered with lids to restrict evaporation, as illustrated in Figure 3.8, and covered with wet burlap. Depending on environmental and weather conditions, samples are either stored in large cooling boxes or left under the wet burlap.

Figure 3.8 Covering Molds with lids to prevent evaporation NJTP interchange 7A

3.2.7 Curing Regimes

After Sampling, all of the cylinders were cured in the environmental temperature and humidity controlled chamber as illustrated in Figure 3.9 for the first 24 hours for initial curing. Conditions in the environmental chamber are maintained 74 degrees Fahrenheit and 50% relative humidity. As an alternative to using wet burlap and to avoid the risk of contact between the burlap and the fresh concrete, the molds were covered with lids to restrict evaporation.

Figure 3.9 Environmental Chamber

3.2.7.1 Moist Curing

The moist curing practice is based on ASTM C511. Samples are stored in the curing room maintained at around 73° F and relative humidity greater than 95% until testing day. Samples are placed away from any sources of water. Figure 3.10 shows the curing room where the samples were cured.

Figure 3.10 Moist Curing Room

3.2.7.2 Lime Bath

Excessive hydrated lime (calcium hydroxide) was dissolved in the water to make a saturated solution. Lime content in the tanks is maintained at 3 g/L in accordance with ASTM C511. Temperature is maintained at 73.5 ± 3.5 °F and galvanized steel tanks were used to avoid corrosion as shown in Figure 3.11. Concrete samples were cured in the lime bath after demolding at 24 hours. Samples were tested at each age after removing the excess water.

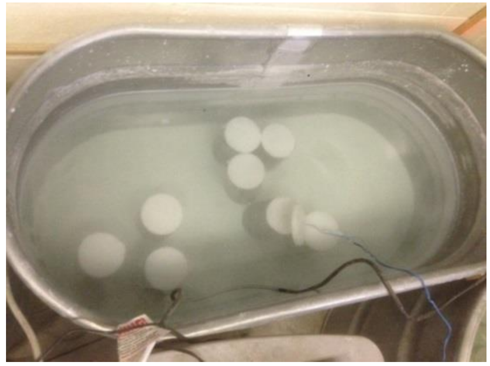

Figure 3.11 Lime Bath Curing

3.2.7.3 Water Bath

ASTM C511 specifies the addition of hydrated lime into water storage tanks illustrated in Figure 3.12. Hydrated Lime was not added into water bath to observe the effect of lime on surface resistivity, rapid chloride permeability and compressive strength. Concrete samples were placed in the water tank when they were demolded after 24 hours. Cylinders were tested at the ages described below when the samples were taken from the bath and the excess water was removed.

Figure 3.12 Water Curing Tanks

3.2.7.4 Accelerated (Hot) Lime Bath Curing

In this method the samples are taken out of the lime bath after seven days in accordance ASTM C1202 and stored in hot lime bath where temperature is maintained at 100 ± 3°F using electric tank heaters. The tanks are fitted with temperature sensors connected to a data logger for continuous temperature monitoring and control.

Figure 3.13 Accelerated (Hot) Lime Bath Curing

3.3 LABORATORY TESTING

Laboratory testing is conducted starting with the identification of coarse and fine aggregate properties essential for mix design, such as moisture content. Other material information is gathered from suppliers. Fresh concrete properties tests are conducted immediately after the final mixing stage. Hardened concrete tests are conducted as specified in each section.

3.3.1 Compressive Strength Test

Figure 3.14 Concrete Compression Machine

Compressive strength tests are conducted at 28 days after casting in accordance with ASTM C39 standards. Two concrete cylinders are tested to ensure uniformity of results. If both cylinders do not yield similar results a third sample is tested and the outlier is discarded. After passing visual inspection, each cylinder is sulfur-capped as specified in ASTM C617 to provide a flat surface for testing in the conditioning phase, shown in Figure 3.15. The sulfur is allowed to harden before the testing phase.

After the conditioning phase, cylinders are placed in the marked center of the loading area, the steel mish door is shut, shown in Figure 3.14, and the piston is lowered until the bearing plate comes in contact with the top of the cylinder. Pressure is then applied at a stress rate of approximately 35 psi/s (400 lb/s). The test concludes when the cracking is observed and the load needle drops below 95% of the peak value and the reading is recorded.

Figure 3.15 Sulfur Capping

3.3.2 RCP Test Procedure

The RCP test is typically conducted at three ages, at 28 days, 56 days and 91 days. Two 4" x 8" concrete cylindrical samples are used to conduct this test. A 1.97 ± 0.12 inch specimen segment is taken from each sample, after removing the top exposed surface, top segment is cut for the 28days test, the following segment for the 56 days test and the bottom segment for the 91 days test. The concrete specimen cutter used is illustrated in Figure 3.16. After placing the specimens into the vacuum desiccator, vacuum in maintained for 120 minutes under dry conditions to aspirate entrapped air. Figure 3.17 illustrates a vacuum pump apparatus setup.

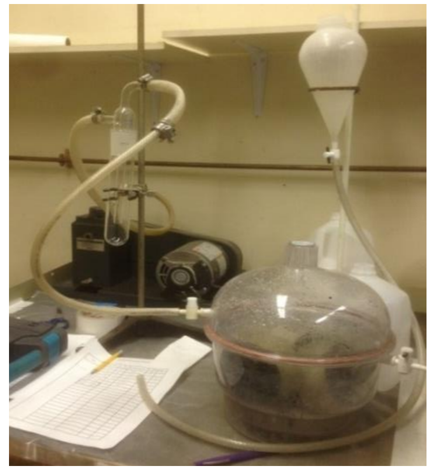

Figure 3.16 Concrete Specimen Cutter **Figure 3.17 Vacuum Pump Setup**

As a purer alternative to preparing deionized water by boiling tap water, distilled water is then added to the vacuum, through water stopcock, until specimens are completely submerged and left with pump on for an additional 60 minutes after which specimens are left to sock between 16 to 20 hours. This procedure insures the removal of ions that would interfere with concrete conductivity.

After this 18 hour period of submergence without vacuuming, the conditioning phase is completed and the specimens are assembled in voltage cells. The cells used for this test were manufactured by Germann Instruments (GI) and are designed to include a plastic ring between two voltage test blocks fitted with rubber washers. This design ensures the specimens are not exposed as an alternative to conventional practice of epoxy coating. This design also includes air vents or cooling fins in each voltage cell block as an answer to skepticism regarding the increase of specimen temperatures in traditional RCPT cell blocks and its effect on the results. The three mentioned parts, two voltage cell blocks and plastic ring with washers, are then tightly screwed together with the specimen enclosed. Both cell blocks include reservoirs where a 3% sodium chloride (NaCl) solution is poured in on one side and a 0.3 N sodium hydroxide (NaOH) solution into the other. The voltage cell blocks are then plugged into the GI proove it device which maintains a 60 V voltage through the cells. A predicted reading is given on the monitor and after six hours the actual reading is displayed after which the test is concluded. The test setup is conducted under room temperature conditions. Figure 3.18 illustrates the final setup for the RCP test.

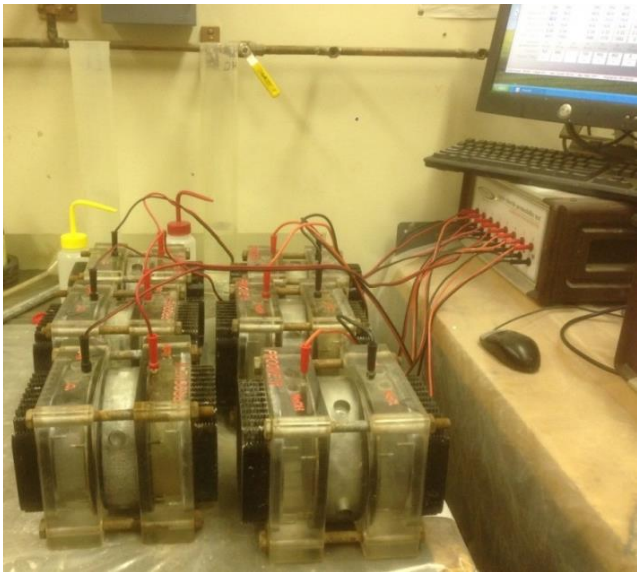

Figure 3.18 Voltage Cell Blacks Assembled and Plugged

3.3.3 SR Test Procedure

The Surface Resistivity (SR) Test is conducted in accordance to AASHTO Designation: TP 95-11. Two 4 x 8 inch samples are used to perform the SR test to ensure consistency. Hot cured samples are placed in room temperature tanks for a period of half an hour to allow the samples to cool down and thus eliminate the effect of temperature on the reading. Also samples cured in the curing room are placed in room temperature tanks to insure they are well saturated before testing. Resipod Resistivity Meter, manufactured by Proceq, measure resistivity through a four-point Wenner probe.

Firstly, the cylinders are labeled at four points around the circumference of the top face 0, 90, 180, and 270 degrees. Next, all four probes of the SR meter are pushed against the longitudinal surface of the cylinder at the 0 degrees mark and once the reading stabilizes the resistivity measurement is recorded. It is important to ensure that all four probes are in contact with a smooth surface of the cylinder while performing the test as illustrated in Figure 3.19 (a) and (b). The same procedure is then repeated for all the marked degrees going around the cylinder twice and recording a total of eight readings.

(a) (b)

Figure 3.19 (a) Surface Resistivity Test (b) Pushing all four probes at marked degrees

3.4 Experimental Program

This section outlines the purpose of each experimental programs included in this study.

3.4.1 Parametric study to investigate the effect of pozzolans and admixtures under different curing regimes

Five mixes were made to develop a parametric study comparing Rapid Chloride Permeability, Surface Resistivity and Compressive Strength cured in three different regimes: Curing Room, Lime Bath and Accelerated (Hot) Lime bath. Pozzolans investigated are Fly Ash and Slag which are used in typical HPC concrete. The following list includes mixtures used for this study:

1. C: Cement Mix
2. SL: Slag Mix
3. FA: Fly Ash Mix
4. RET: Fly Ash and Retarder Mix
5. ACC: Fly Ash and Accelerator Mix

Mix Design Table Abbreviations:

PC=Portland Cement, SF=Silica Fume, FA=Fly Ash, SL=Slag, AEA=Air Entraining Agent, HRWR=High Range Water Reducer or Super-plasticizer, WR=Workability Retaining admixture (retarder), ACC = Accelerator

Table 3.1 Laboratory Mix Design and Fresh Concrete Properties

	Note	**C**	**SL**	**FA**	**RET**	**ACC**	**T**
Date		10/1/2014	10/2/2014	10/2/2014	10/3/2014	10/3/2014	5/5/2014
PC, lb.	Type I	55.5	36.63	45.15	45.2	45.15	39.65
SF, lb.	-	0	2.13	2.15	2.15	2.15	0.00
FA, lb.	Class F	0	0	8.10	8.10	8.10	0.00
SL, lb.	Grade 100	0	16.61	0	0	0	26.45
Gravel, lb.	#57	154.35	153.5	153.25	153.15	153.25	180.30
Sand, lb.	-	103.75	102.75	101.8	101.8	101.8	120.25
Water, lb.	w/c=0.4	20.55	20.6	20.65	21.0	20.65.	26.85
AEA, ml	Section 6A	25.0	25.0	25.0	25.0	25.0	20
HRWR, ml	Chem strong SP	131	131	131	131	131	49
RET, ml	Chem strong R	-	-	-	131	-	MRWR : 49 (Chem strong A)
ACC , ml	Chem strong CF	-	-	-	-	491	49
Air	%	8.5	7.0	6.5	7.5	5.5	7.5
Slump	in	6.5	5.5	7.5	7.0	7.0	4.5

3.4.1.1 Effect of Pozzolans on Surface Resistivity and Rapid Chloride Permeability

The three mixes for this comparison are the Cement (C) control mix, Slag (SL) mix, Fly Ash (FA) mix.

3.4.1.2 Effect of Retarder and Accelerator admixtures on Surface Resistivity and Rapid Chloride Permeability:

The three mixes for this comparison are:

1. FA: Fly Ash Mix
2. RET: Fly Ash and Retarder Mix
3. ACC: Fly Ash and Accelerator Mix

3.4.2 Investigate the effect of curing regimes on field samples

Ten HPC field mixes were collected from various locations in New Jersey during concrete pours to investigate the effect of curing regimes on Rapid Chloride Permeability, Surface Resistivity and Compressive Strength. Samples were cured in three different regimes: Curing Room, Lime Bath and Accelerated (Hot) Lime bath. Mix proportions of filed mixes are listed in Table 3.7. For grouped mixes the air and slump test are with ± 1 unit.

Mix Design Table Abbreviations:

PC=Portland Cement, SF=Silica Fume, FA=Fly Ash, SL=Slag, AEA=Air Entraining Agent, HRWR=High Range Water Reducer or Super-plasticizer, WR=Workability Retaining admixture (retarder), ACC = Accelerator

Table 3.2 Field Mix Design and Fresh Concrete Properties

	Note : per cu.yd	**S**	**CLS**	**ES**	**7A1 / 7A2 /TP53/RU**	**HES 16,19,23**
Date/ Location		9/26/2014, El Sol Contracting, Jersey City,	9/30/2014 Clayton Plant,Edison	10/2/2014, Eastern Concrete Materials, Jersey City	10/21/2014, NJTA interchange 7A	June 16,19,23/ 2014 Jersey City
PC (Type I)	Essroc cement company	565 lb	427 lb	585 lb	501 lb	535 lb
SF	Norehem inc. /RHEOMAC, SF 100 MB	25 lb	75 lb	75 lb	25 lb	25 lb
FA	Proash STI Class F	0 lb	0 lb	0 lb	132 lb	140 lb
SL (#100)	Lafarge Grade 100	106.67 lb	765 lb	1315 lb		
Gravel (#57)	Tilcon /Pennington trap rock	1800 lb	1780 lb	1800 lb	1850 lb	1800 lb
Sand	Eastern Concrete Materials / Clayton's sand	1271.17 lb	1200 lb	1233 lb	1184 lb	1173 lb
water		16.47 gal w/c=0.314	24 gal w/c=0.39	22.13 gal	31.15 gal w/c=0.4	w/c = 0.28
AEA	BASF MasterAir® AE 200/MBVR	3.67 oz	5.5 oz	8 oz	6.6 oz	12 oz
Superplasticizer HRWR	BASF MasterGlenium® 7500/Glenuim	50 oz	76 oz	89 oz	79 oz	50 oz
WR	MasterSure® Z 60	24 oz	16 oz	12.67 oz	19.7 oz	56 oz
ACC.	Master Builder Non Calcium Chloride	280 oz	-	-	-	280 oz
Air	%	4.0	6.4		5.7	8.0
Slump	in.	3.5	6.25	6.0	6.5	7.87

3.4.3 Investigate the correlation between RCP and SR test results under different curing regimes

In this investigation the RCP and SR testing results correlation is developed at the following curing ages:

1. RCPT at 28 days and SRT at 28 days.
2. RCPT at 56 days and SRT at 56 days.

A conclusion can be drawn from the difference in correlation between moist curing and lime bath curing versus hot lime bath curing, regarding whether the compilation of both results for a correlation will reflect an accurate correlation.

3.4.4 Effect of Curing Conditions on SRT and RCPT Results

To study the effect of lime curing on SRT and RCPT results, one mix was reproduced in the civil laboratory and the SRT and RCPT were performed on the samples accordingly. The reproduced mix design named “T” is summarized in Table 3.1. A total of 25 concrete cylinders (4 in. x 8 in.) were cast and cured in the laboratory. All concrete samples were demolded and cured in two (2) different curing baths.

(1) **Water bath with lime (lime bath):** Excessive hydrated lime (calcium hydroxide) was dissolved in the water to make a saturated solution. Concrete samples were cured in the lime bath after demolding at 24 hours. Samples were tested at each age after removing the excess water.

(2) **Water bath without lime (water bath):** No lime was added in the water bath. Concrete samples were placed in the water tank when they were demolded after 24 hours. Cylinders were tested at the ages described below when the samples were taken from the bath and the excess water was removed.

3.4.5 Compilation of laboratory and field mixtures

To draw a correlation from a larger sample size, in this investigation the RCP and SR testing results correlation is developed for both field and laboratory samples at the following curing ages:

1. RCPT at 28 days and SRT at 28 days.
2. RCPT at 56 days and SRT at 56 days.

From this correlation the surface resistivity limits can be drawn and a comparison with published studies and reports that include both laboratory and field mixes would be more accurate.

CHAPTER IV

4 RESULTS

The purpose of this chapter is to present a summary of the data and findings of the hardened concrete testing for laboratory and field mixes. Results include strength, rapid chloride permeability and surface resistivity. The collected data can be seen in Tables 4.1, 4.2 and 4.3.

Two curing and conditioning procedures were followed; the difference between the two methods is the duration of hot curing and sample usage. In the first procedure the hot curing samples remained in the hot curing tank until testing day. Also for consistency, the same samples that the SR test was performed on were then cut for the RCP test. Mixes tested using this procedure are T, 7A1, 7A2, HES 16, HES 19, HES 23 and RU.

In the second procedure, the hot curing was for a duration of 14 days after which samples were submerged in the room temperature curing tanks. In this procedure the samples were designated for strictly SR test and strictly RCP test.

Table 4.1 Laboratory Samples RCPT and SRT Results

Age		7	14	28	56	91	28	56	91
Mix	**Curing Regime**	**Surface Resistivity (kohm-cm)**					**Rapid Chloride Ion Penetration (coulombs)**		
T	Curing Room	9.9	17.4	20.5	27.2	29.2	1703	1452	960
	Lime Bath	6.8	12	15.9	21.6	24.6	2646	1748	1459
	Water Bath	6.8	12.9	15.2	22.3	26.7	2109	1811	1532
	Hot Lime	6.8	13.1	16.3	26.3	32.9	1334	1052	938
C	Curing Room	14.3	16.6	18.5	23.3	24.7	2345	2065	1912
	Lime Bath	11.5	15.2	18.6	23.3	22.4	2275	2268	1975
	Hot Lime	12.3	17.1	25.3	24.6	23.4	1595	1962	1784
SL	Curing Room	21.6	26.6	40.6	69.8	75.5	1435	632	616
	Lime Bath	18.4	25.8	41.8	67.8	72.8	1188	628	576
	Hot Lime	18.0	59.3	78.1	82.4	87.3	612	530	463
FA	Curing Room	11.6	15.6	28.3	39.4	53.8	1949	1032	850
	Lime Bath	10.3	13.9	27.3	39.7	47.9	2120	1033	770
	Hot Lime	8.7	44.7	71.3	62.3	70.3	663	610	510
RET	Curing Room	7.1	10.6	23.5	28.1	42.0	2615	2075	1587
	Lime Bath	5.7	8.0	21.1	21.5	32.6	3642	2195	1520
	Hot Lime	5.1	21.6	51.5	42.0	45.5	1776	1608	823
ACC	Curing Room	9.4	13.1	29.3	33.4	49.6	2144	1145	908
	Lime Bath	9.3	12.7	27.6	33.3	49.2	1994	1154	935
	Hot Lime	9.1	31.8	66.3	57.6	63.0	840	866	682

Table 4.2 Field Samples RCPT and SRT Results

Age		7	14	28	56	91	28	56	91
Mix	**Curing Regime**	**Surface Resistivity (kohm-cm)**					**Rapid Chloride Ion Penetration (coulombs)**		
7A1	Curing Room	7.4	11.4	16.7	39.5	46.9	2416	1108	916
	Hot Lime	6.8	28.1	38.4	59.1	82.5	750	434	391
7A2	Curing Room	7.4	10.8	16.6	37.9	48.2	2433	1173	692
	Hot Lime	6.4	21.0	37.1	62.5	83.8	778	476	345
HES16	Hot Lime	15.5	134.3	146.2	156.9	163.5	201	172	146
HES19	Curing Room	18.4	44.4	79.9	121.0	137.3	470	295	214
HES23	Curing Room	23.5	42.5	72.6	104.2	126.9	483	286	253
S	Curing Room	16.1	23.6	42.5	66.6	74.5	937	728	760
	Lime Bath	15.1	22.4	38.8	66.3	72.6	1239	670	695
	Hot Lime	16.2	51.8	66.7	80.8	87.0	571	529	564
TP53	Curing Room	6.2	9.2	16.4	35.7	39.6	2314	1365	985
	Lime Bath	7.0	9.7	17.9	35.1	40.9	3088	1282	1080
	Hot Lime	7.5	22.9	52.1	61.8	63.6	591	686	560
RU	Lime Bath	5.0	9.9	19.3	28.6	40.1	2238	1154	982
	Hot Lime	5.9	32.8	37.2	46.3	77.5	N.A.	N.A.	N.A.
CLS	Curing Room	13.5	17.6	22.6	33.8	36.1	2331	1106	1352
	Lime Bath	12.9	16.7	20.3	32.9	33.0	1784	1113	1331
	Hot Lime	12.4	26.9	38.5	39.1	39.0	1432	1166	1214
ES	Curing Room	8.9	13.6	29.7	46.6	54.6	1672	1008	809
	Lime Bath	7.2	12.4	28.2	48.5	53.9	1926	1033	836
	Hot Lime	7.8	12.8	51.8	56.6	64.5	1065	876	729

Table 4.3 28 day Compression Test Results f'c (psi)

Field Mixes		TP53			ES		
Curing Method	Curing Room	5317.47			5650		
	Lime Bath	5476.2			5849		
	Hot Lime Bath	6051			6167		
Laboratory Mixes		**T**	**C**	**SL**	**FA**	**ACC**	**RET**
Curing Method	Curing Room	5728	3326	3438	3342	4218	2053
	Lime Bath	6524	3541	3692	3470	4393	2180
	Hot Lime Bath	6722	4138	4281	3955	4616	2666

The NJDOT design and verification requirement for HPC compressive strength at 56 days is 5400 psi and if achieved at 28 days then it is accepted. In this study the compressive strength test was conducted at 28 days.

Table 4.4 28 day Compression Test Results T Mix

Laboratory Mix T	
Curing Regime	**f'c (psi)**
Curing Room	5727.92
Water Bath	6364.36
Lime Bath	6523.47
Curing Room to Hot Water Bath	6443.91
Water Bath to Hot Water Bath	7358.79
Curing Room to Hot Lime Bath	6404.14
Lime Bath to Hot Lime Bath	6722.35

CHAPTER V

5 EVALUATION OF RESULTS

In this chapter results will be evaluated and analyzed in a readable format to draw conclusions and comparisons. For simplicity in some graphs both lime bath curing and moist curing are grouped and referred to as cold curing. This does not indicate lower temperature of curing than specifications, but merely as a distinction when comparing with accelerated (hot) curing. Regarding the SR and RCP correlation, they were studied at three different ages to investigate which age gives the highest correlation before drawing conclusions.

5.1 SR versus Age graph for laboratory mixes

This section is to observe the effect of curing regimes on surface resistivity. The first graph is a compilation of laboratory mixes which illustrates SR results in different curing regimes.

5.1.1 Parametric study graphs:

5.1.2 Effect of pozzolans:

i. Control Mix: C

ii. Slag Mix : SL

iii. Fly Ash Mix : FA

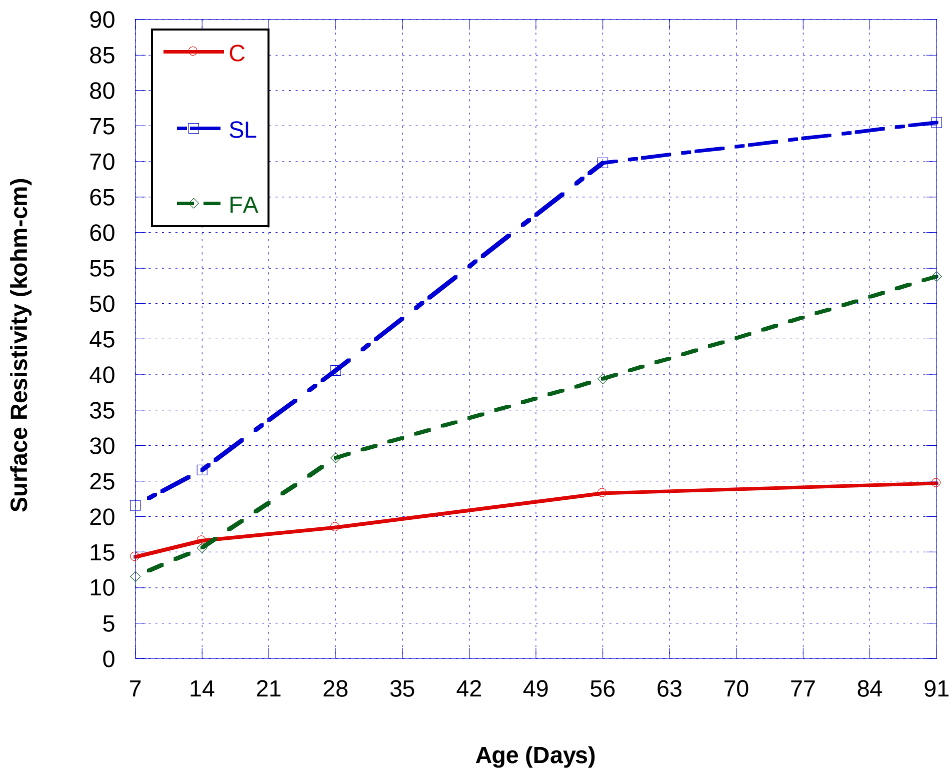

Figure 5.1 Effect of Slag and FA on SRT Results – Moist Curing

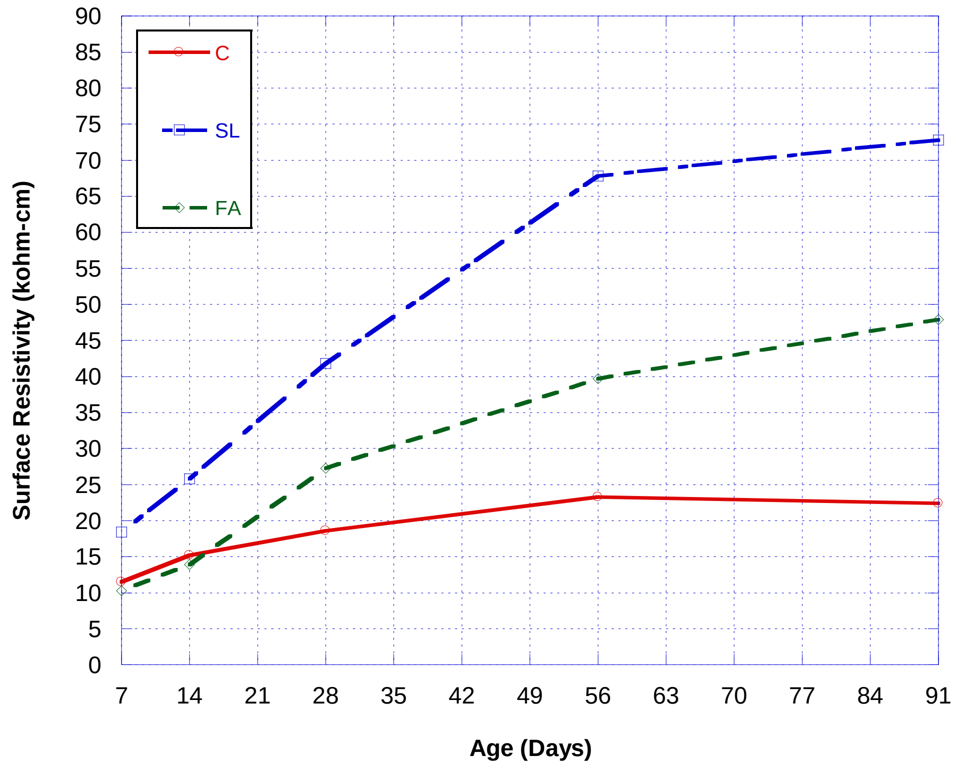

Figure 5.2 Effect of Slag and FA on SRT Results – Lime Bath

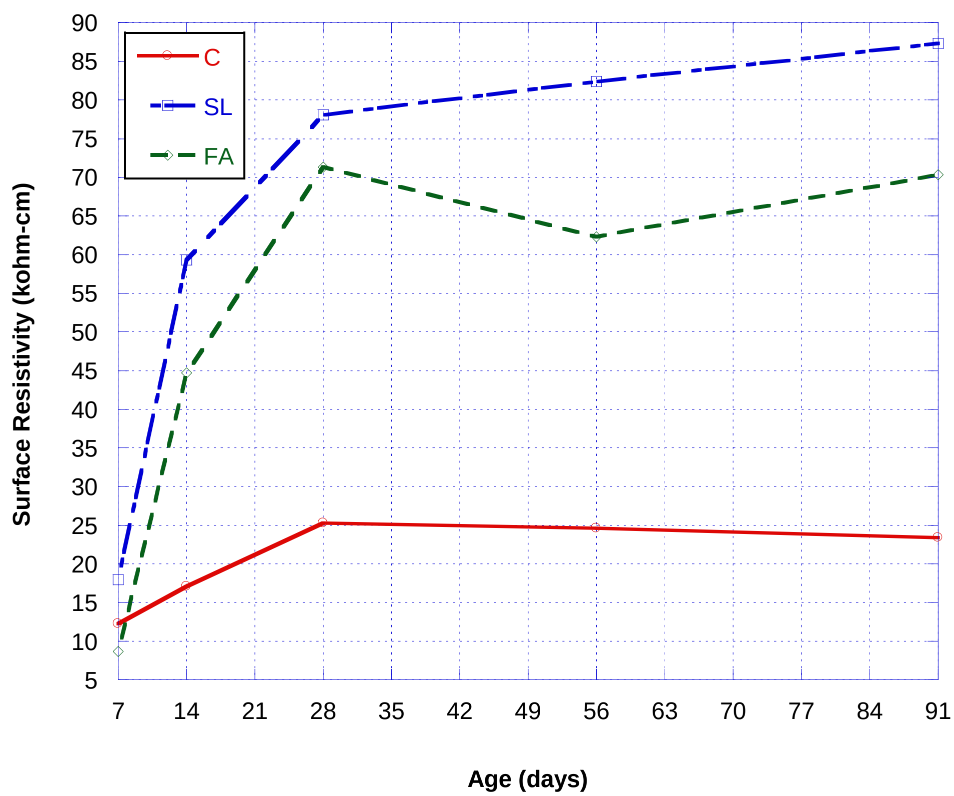

Figure 5.3 Effect of Slag and FA on SRT Results – Hot Lime

Results presented in this section indicate that at the presence of Slag favorably impacts the surface resistivity of concrete. While the effect of Fly Ash did not significantly impact concrete durability in moist and lime bath curing 14 days, its effect is evident in hot lime curing. At 28 and 56 days the FA mix exceeded the control mix surface resistivity. A possible explanation is the slower reaction time of fly ash which appears to be accelerated in hot lime curing which decreases at 56 days after removal from the hot lime bath. As opposed to the significant increase in SRT reading and durability from 28 days to 56 days, a minimal increase at an average of around 8.0 kohm-cm is recorded between 56 days and 91 days. This minor increase in durability suggests that the pozzolans have reached, or are very close to reaching, their reaction time.

5.1.3 Effect of admixtures:

i. Fly Ash Mix : FA (Control)

ii. Accelerator and Fly Ash Mix : ACC

iii. Retarder and Fly Ash Mix : RET

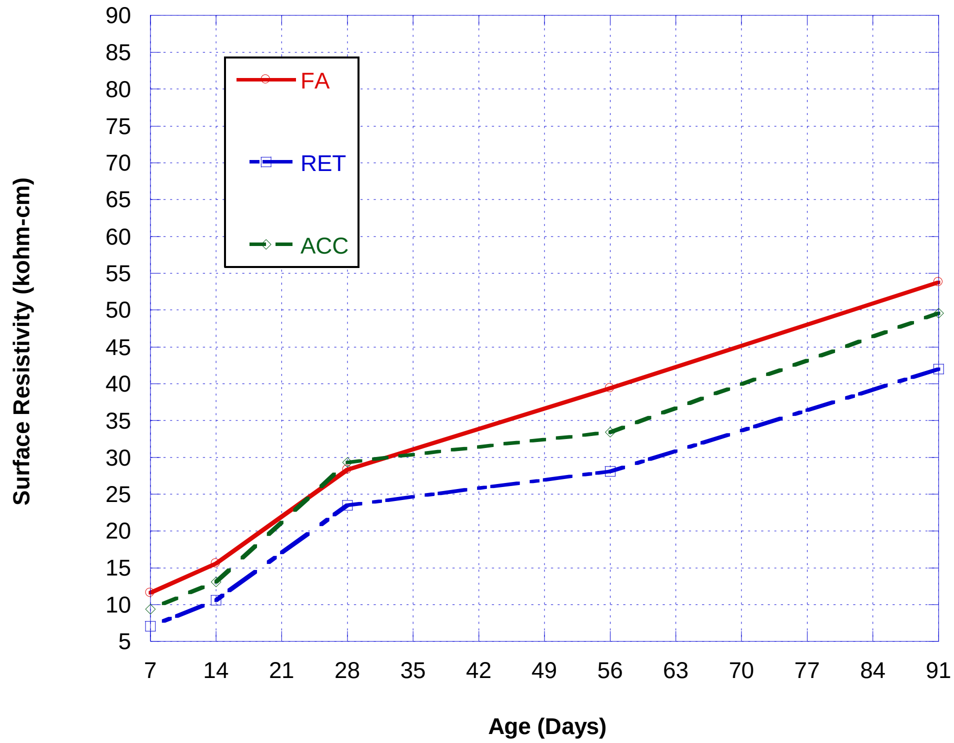

Figure 5.4 Effect of Retarder and Accelerator on SRT Results – Moist Curing

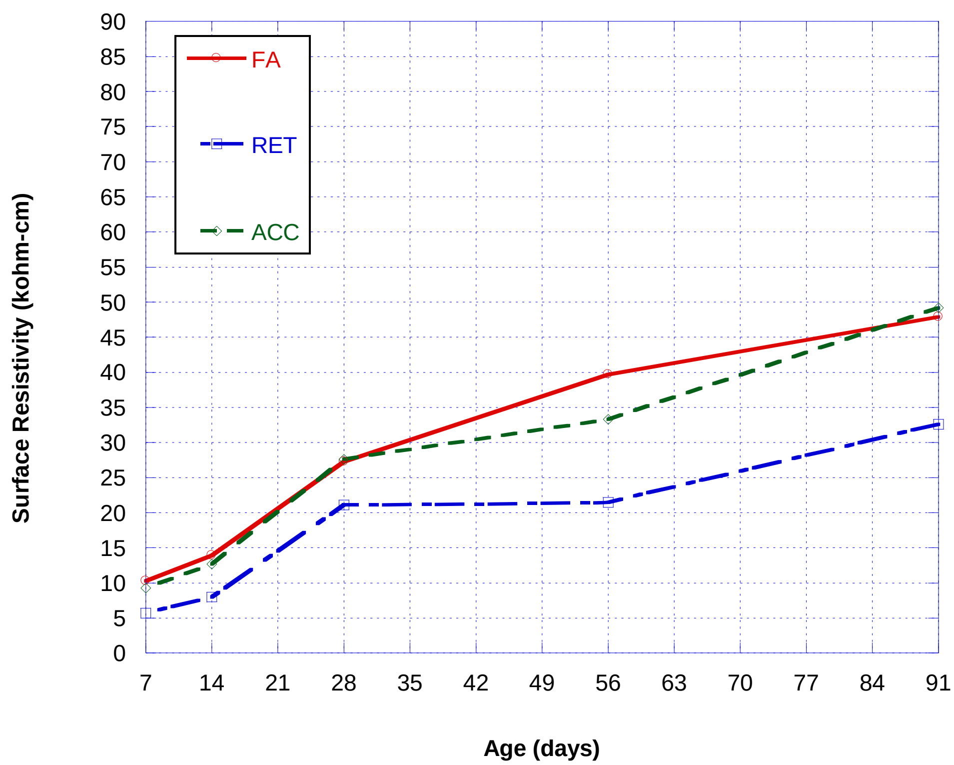

Figure 5.5 Effect of Retarder and Accelerator on SRT Results – Lime Bath

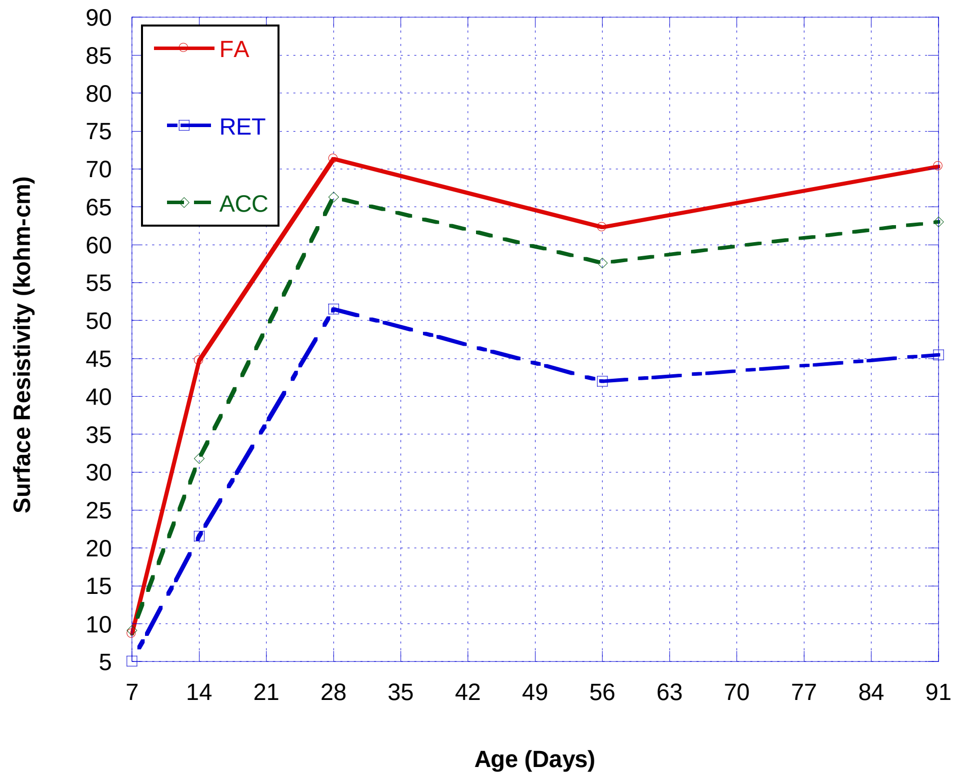

Figure 5.6 Effect of Retarder and Accelerator on SRT Results – Hot Lime

Results presented in this section indicate, as expected, the accelerating admixture applied favorably impacted the surface resistivity of concrete while the mix with the retarding admixture has lower durability than the control mix. However at 56 days the control mix demonstrated higher durability than both retarder and accelerator mixes. While such chemical admixtures may achieve the desired fresh concrete properties, it may be concluded that such chemical admixtures are not effective for achieving higher durability. Similar results and trends are observed for moist curing and lime bath curing; however the trend changes in hot curing where the surface resistivity results decreased at 56 days compared to 28 days. SRT readings continue to increase at 91 days in moist and lime bath curing conditions, while at 91 days the highest readings obtained at earlier ages were almost achieved at 91 days. The trend observed in hot curing may be attributed to the temperature of the cylindrical specimen at the time of testing.

5.2 RCP versus Age graph for laboratory mixes

This section is to observe the effect of curing regimes on rapid chloride permeability. The first graph is a compilation of laboratory mixes which illustrates RCP results in different curing regimes.

5.2.1 Parametric study graphs:

5.2.2 Effect of pozzolans:

i. Control Mix: C

ii. Slag Mix : SL

iii. Fly Ash Mix : FA

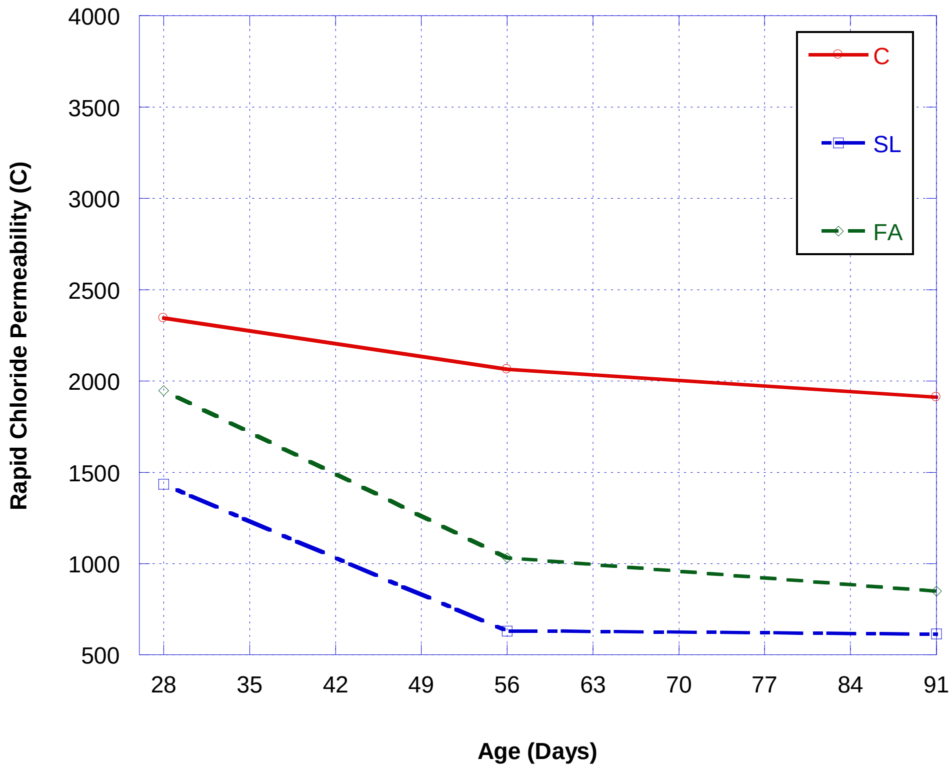

Figure 5.7 Effect of Slag and FA on RCPT Results – Moist Curing

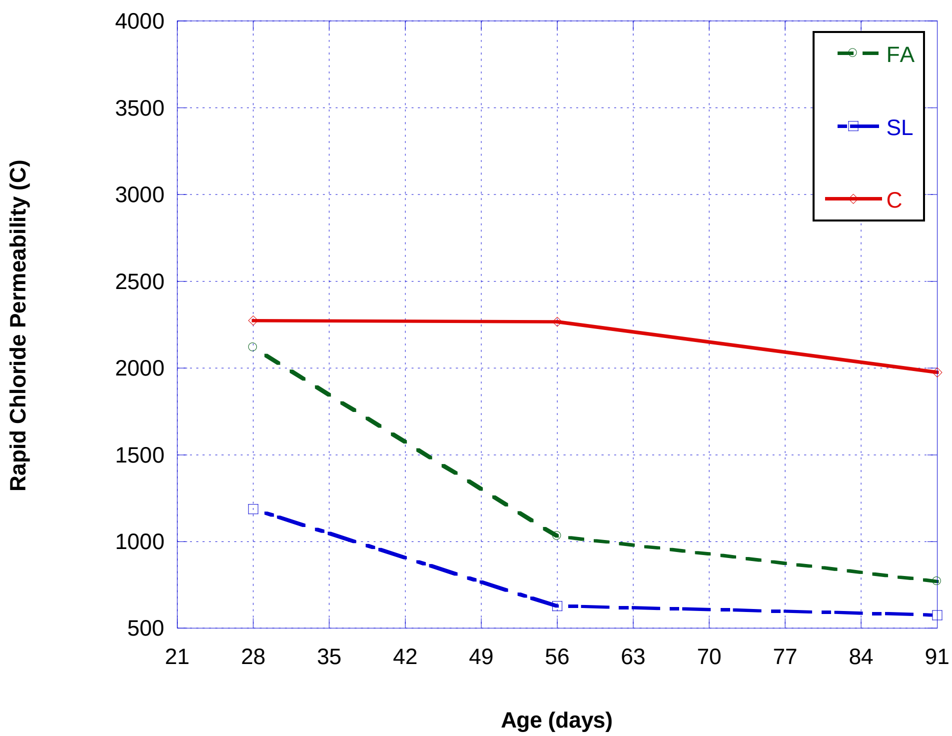

Figure 5.8 Effect of Slag and FA on RCPT Results – Lime Bath

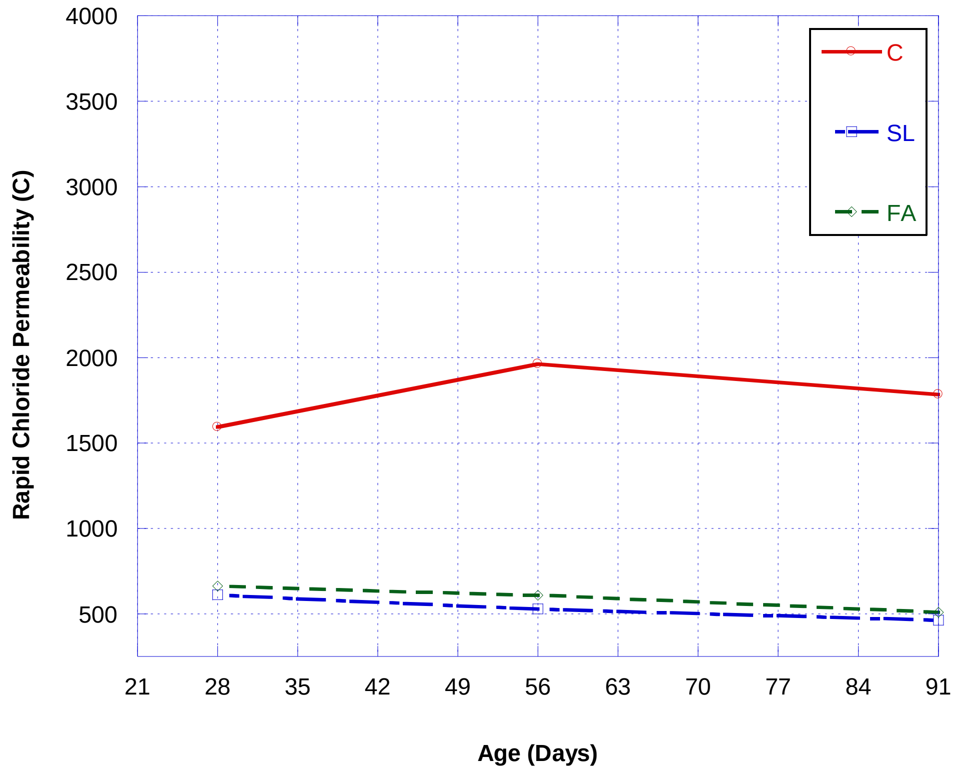

Figure 5.9 Effect of Slag and FA on RCPT Results – Hot Lime

Results presented in this section indicate that at the presence of Slag and Fly Ash favorably impact the rapid chloride permeability of concrete. While the effect of Fly Ash did not significantly impact concrete durability in moist and lime bath curing 28 days, its effect is evident in hot lime curing. A similar trend can be observed in all three curing methods however the rapid chloride permeability of the control mix increased after removal from the hot lime bath.

5.2.3 Effect of admixtures:

iv. Fly Ash Mix : FA (Control)

v. Accelerator and Fly Ash Mix : ACC

vi. Retarder and Fly Ash Mix : RET

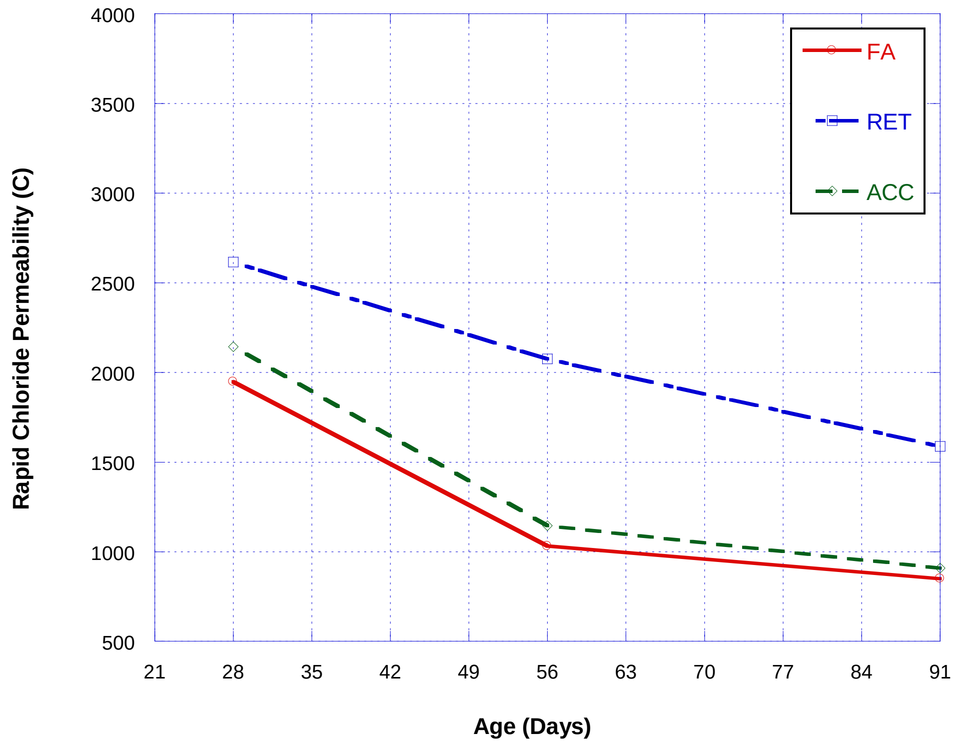

Figure 5.10 Effect of Retarder and Accelerator on RCPT Results – Moist Curing

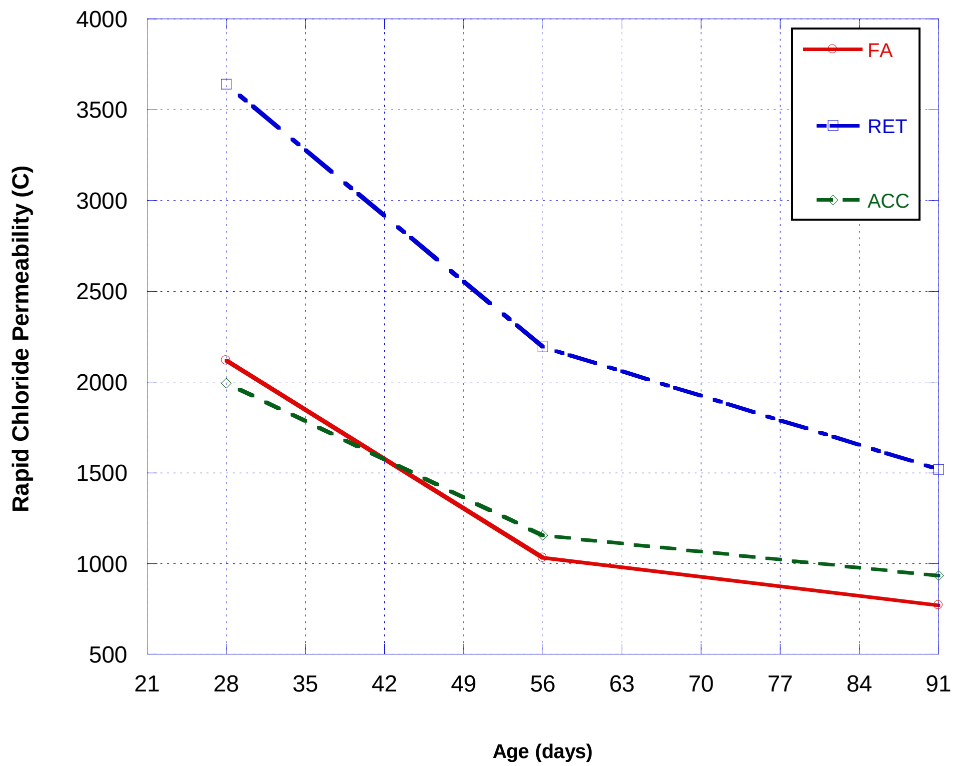

Figure 5.11 Effect of Retarder and Accelerator on RCPT Results – Lime Bath

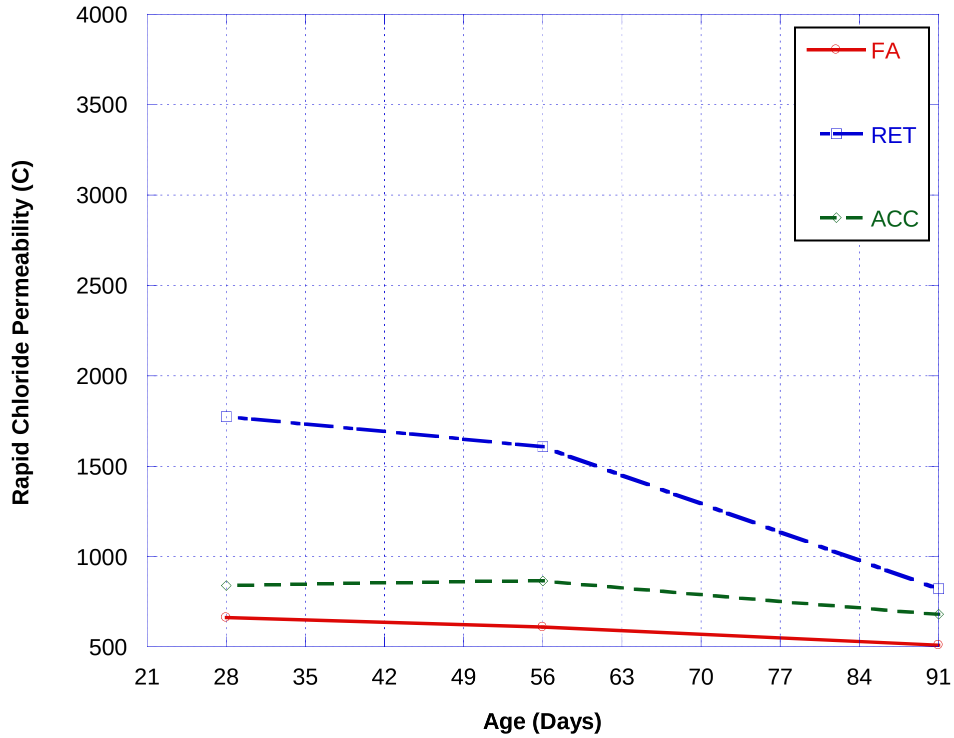

Figure 5.12 Effect of Retarder and Accelerator on RCPT Results – Hot Lime

Results presented in this section indicate, as expected, the accelerating admixture applied favorably impacted the rapid chloride permeability of concrete while the mix with the retarding admixture has lower durability than the control mix. The FA and ACC mixtures yielded close results in all curing methods. The control mix demonstrated higher durability than both retarder and accelerator mixes. While such chemical admixtures may achieve the desired fresh concrete properties, it may be concluded that such chemical admixtures are not effective for achieving higher durability. Similar results and trends are observed for moist curing and lime bath curing; however the trend changes in hot curing where the results slightly increased at 56 days after removal from the hot lime bath and finally decreased at 91 days.

5.3 Effect of Lime Curing on SR and RCP

Concrete samples were tested at 7, 14, 28, 56 and 91 days for SRT, and at 56 and 91 days RCPT. Tables 5.1 and 5.2 show the testing results for SRT and RCPT, respectively. Figure 5.13 shows the difference in SR readings between the concrete samples cured in the water with and without lime. The maximum difference is 8.19% at 91 days with an average difference of 4.66%. Figure 5.13 shows that the SR readings for the two curing regimes are very well correlated (R^2=0.988), but the water curing slightly overestimated the SR compared to lime curing. Also, Figure 5.14 shows that the error of lime water curing is smaller than that of water curing without lime by 2.85% (0.27% vs. 3.11%), and the SR is more fluctuated if the samples were cured in water bath comparison with lime water curing. Therefore, it can be inferred that the lime has little or minimal effect on the SR measurements (between lime bath and water bath), however, it is recommended to cure all samples in a lime water bath for consistency.

The RCPT results summarized in Table 5.2 show that the concrete samples in water bath attained slightly higher rapid chloride permeability at 56 days (about 3.6%) and 91 days (about 4.3%) compared to those cured in lime bath. Similar permeability between curing regimes was expected that there would be a higher difference in the RCPT readings between the two curing regimes that would be attributed to the fact that the Ca+ ions in the concrete might react with water in the water bath while the ions were conserved in the lime bath. This expectation does not seem to be supported by the results at 56 days and 91 days results of the RCPT readings.

Table 5.1 Surface Resistivity Results (unit: kΩ-cm)

	Curing method		
Age at testing	**Water Bath w/ Lime**	**Water Bath (no lime)**	
			% Difference
7 days	6.8	6.8	0.00%
14 days	12.0	12.9	-7.50%
28 days	15.9	15.2	4.40%
56 days	21.6	22.3	-3.24%
91 days	24.6	26.7	-8.19%
		Average	4.66%

Table 5.2 Rapid Chloride Permeability Results (unit: coulombs)

	Curing method		
Age at testing	**Water Bath w/ Lime**	**Water Bath (no lime)**	
			% Difference
56 days	1748	1811	3.60%
91 days	1459	1523	4.29%

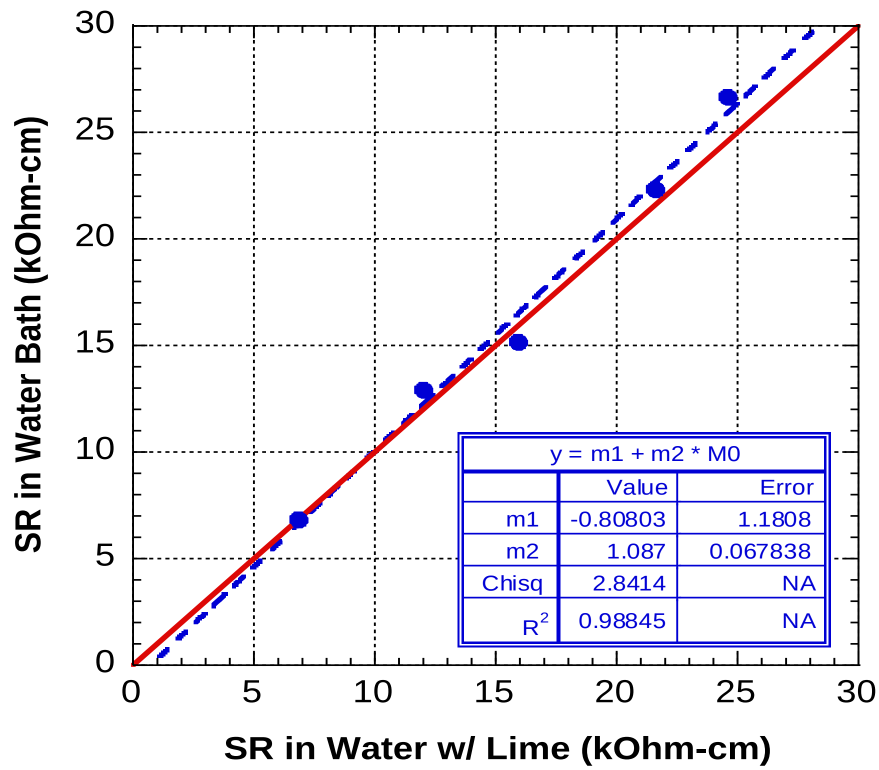

Figure 5.13 Correlation between curing regimes

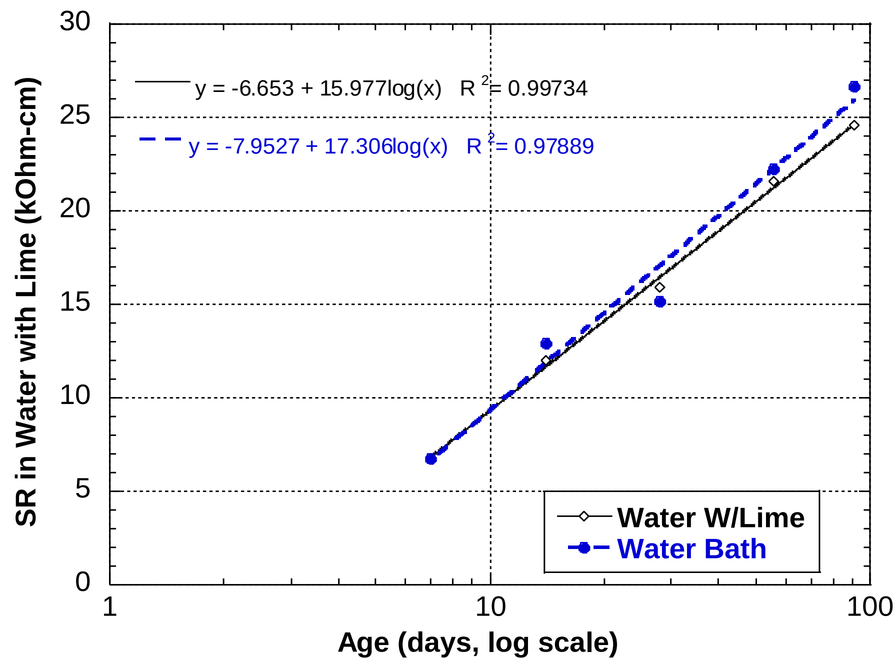

Figure 5.14 Correlation between SR and Age

It is observed that the lime does not have a major effect on the surface resistivity and rapid chloride permeability compared to normal water curing. However, the water curing without lime would slightly overestimate the surface resistivity readings with slightly larger fluctuation in comparison with lime water curing. The fluctuation is not affecting the regression model used in correlating the RCPT and SRT.

5.4 Strength Curing Regime bar chart

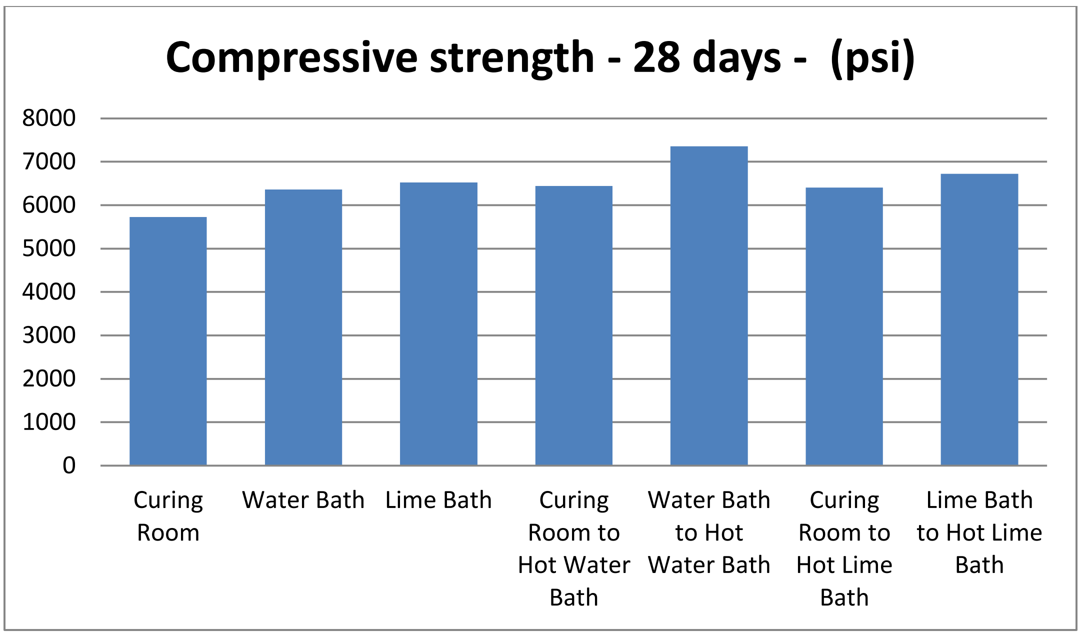

Figure 5.15 Compressive Strength for T mix in various curing Regimes

It can be concluded from Figure 5.15 that for the T mix, hot water curing regime yielded the highest strength with an increase of around 30%. The NJDOT design and verification requirement for HPC compressive strength at 56 days is 5400 psi and if achieved at 28 days then it is accepted. (NJDOT, 2007) In this study the compressive strength test was conducted at 28 days.

5.5 RCP and SR Correlation for each curing regime

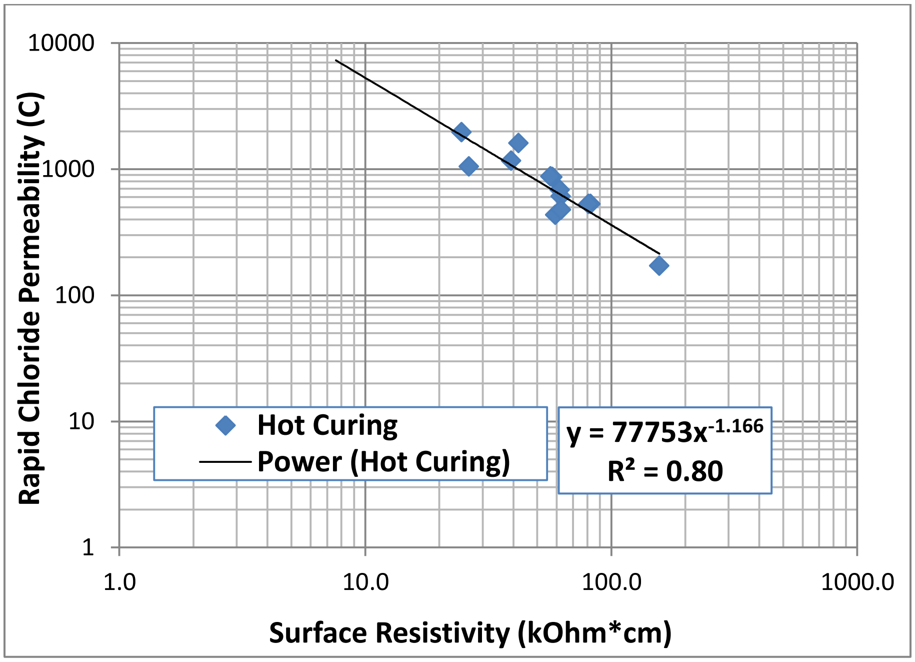

Figure 5.16 RCP (56 Day) vs. SR (56 Day) – Hot

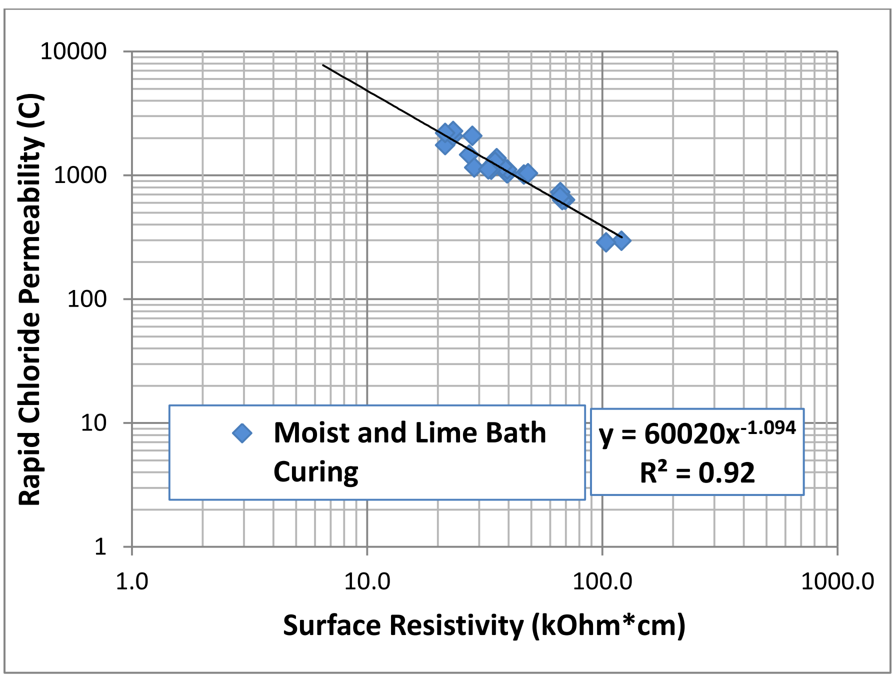

Figure 5.17 RCP (56Day) vs. SR (56 Day) – Moist and Lime Bath Curing

From Figures 5.16 and 5.17 it can be observed that a higher coloration was achieved with samples curing in the curing room and lime bath than samples cured in the hot lime bath. This may be due to the different rate of activation of supplementary cementitious material in HPC in hot curing.

5.6 Surface Resistivity versus Age

The purpose of the graphs presented in this section is to visually and numerically observe at which age the SR results of hot curing are most comparable to moist curing results.

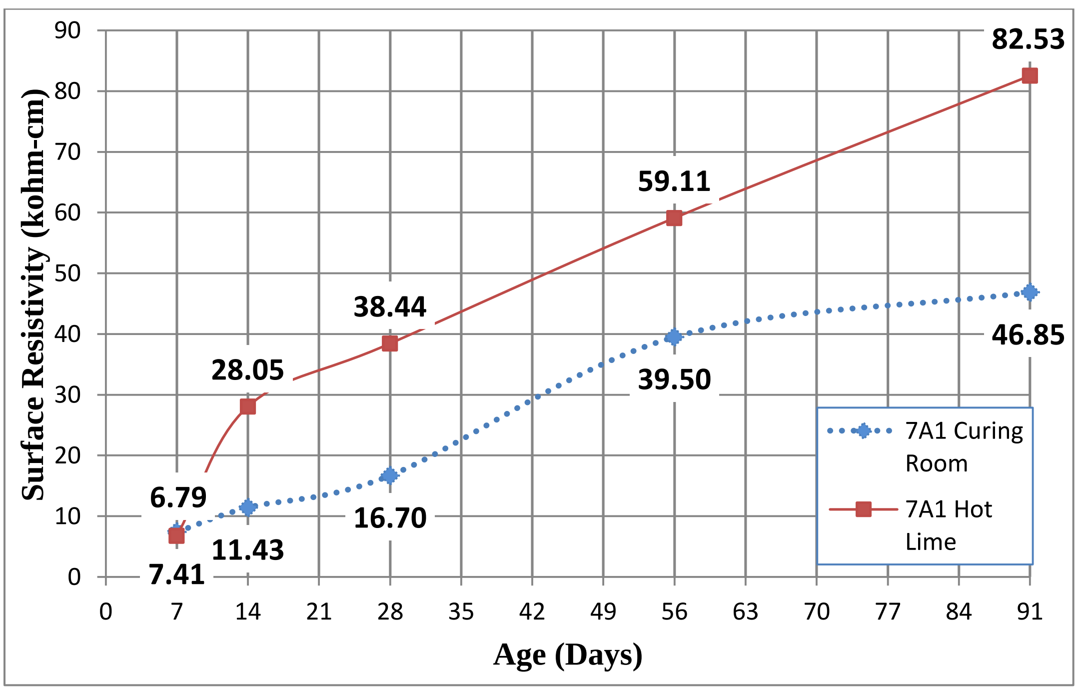

Figure 5.18 Surface Resistivity versus Age - 7A1 mixture

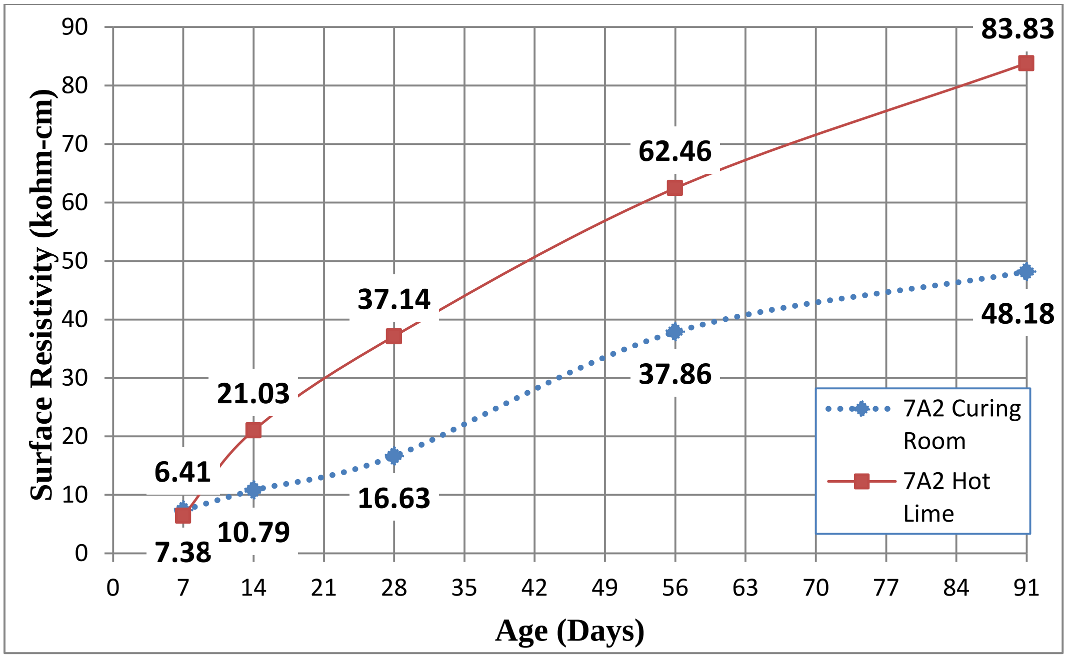

Figure 5.19 Surface Resistivity versus Age - 7A2 mixture

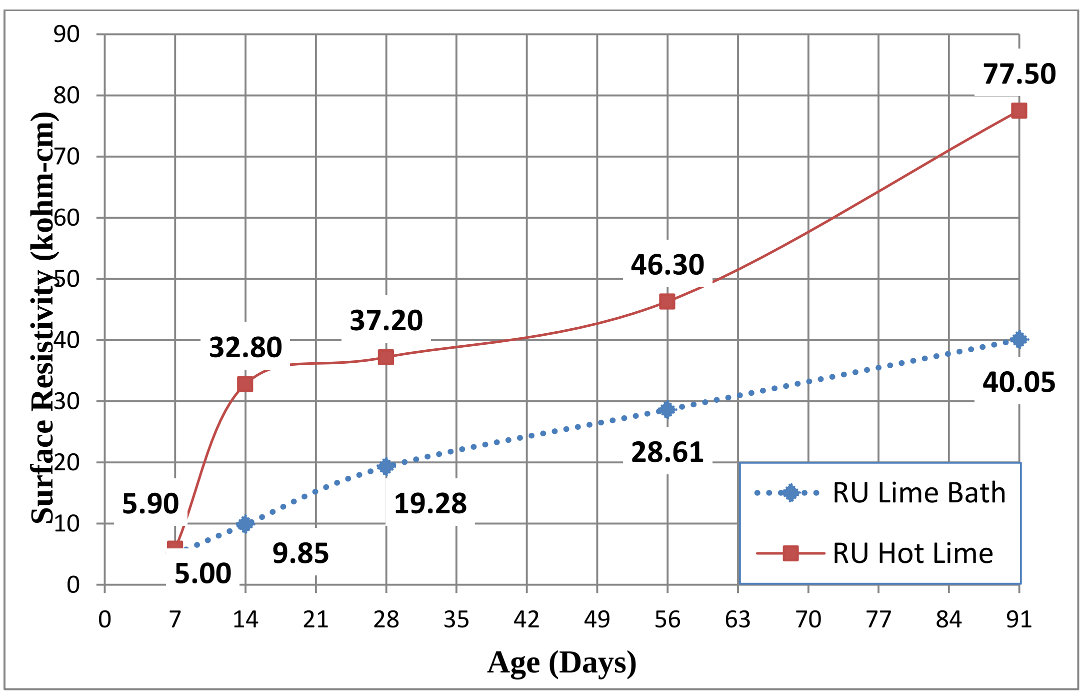

Figure 5.20 Surface Resistivity versus Age - RU mixture

In Figures 5.18 and 5.19, the SR test results of hot curing at 28 days are most comparable to SR test results of moist curing at 56 days. However in Figure 5.20 the SR test results of hot curing at 28 days are most comparable to SR test results of moist curing at 90 days. Three mixes were used to demonstrate the graphs of the trend line, however in section 5.7 more mixes are considered and specific percentage differences are illustrated.

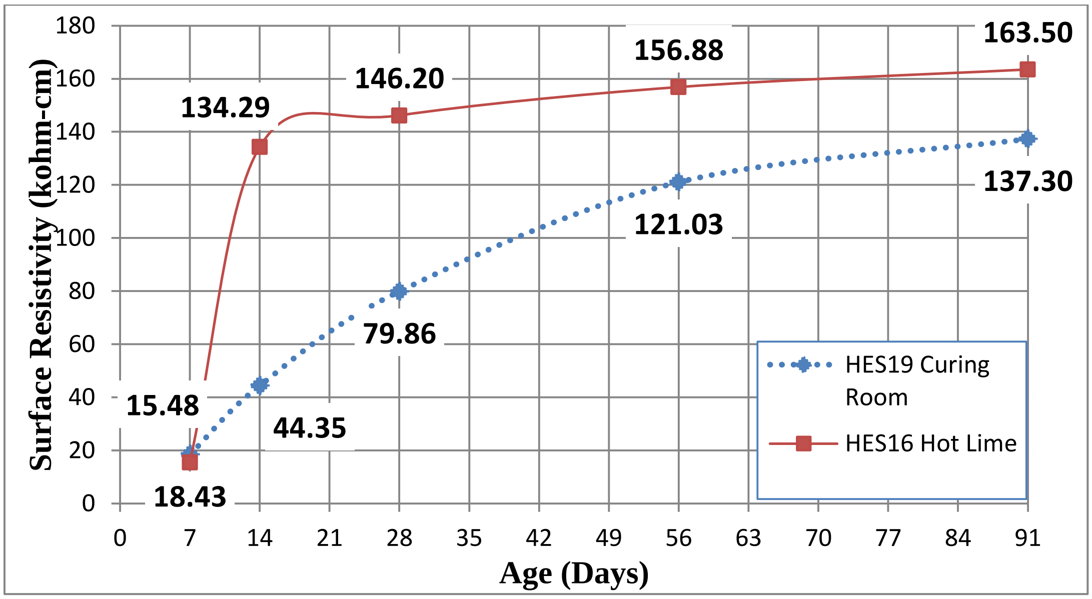

Figure 5.21 Surface Resistivity versus Age - HES mixture

For concrete mixture designed to attain higher early strength as in mixtures HES , Figure 5.26 , the SR test results of hot curing at 14 days are most comparable to SR test results of moist curing at 90 days. It can be concluded that accelerated curing affects SR results of HES-HPC at a faster rate than regular HPC.

5.7 Rapid Chloride Permeability versus Age

The purpose of the graphs presented in this section is to visually and numerically observe at which age the RCP results of hot curing are most comparable to moist curing results.

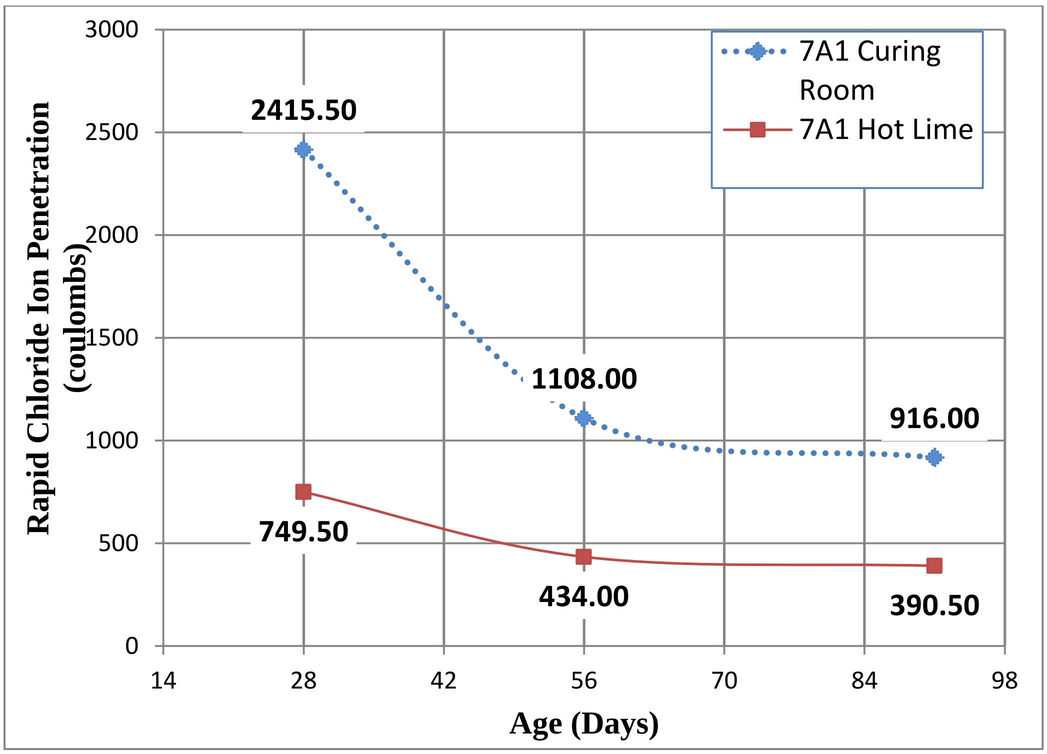

Figure 5.22 RCP versus Age 7A1 mixture

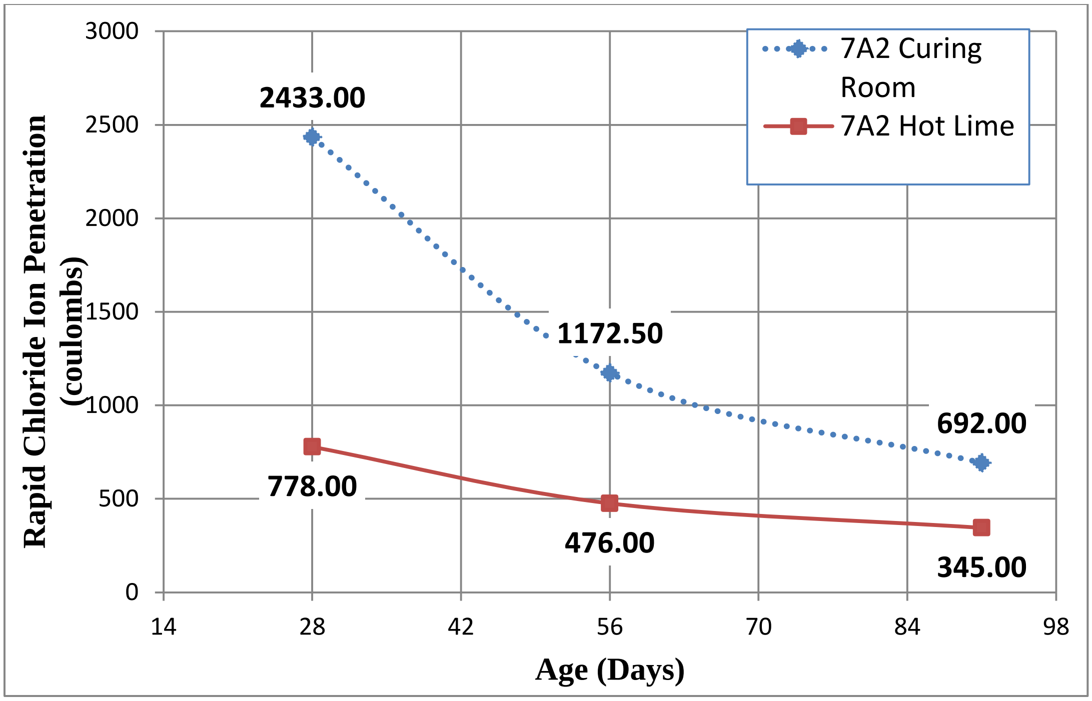

Figure 5.23 RCP versus Age 7A2 mixture

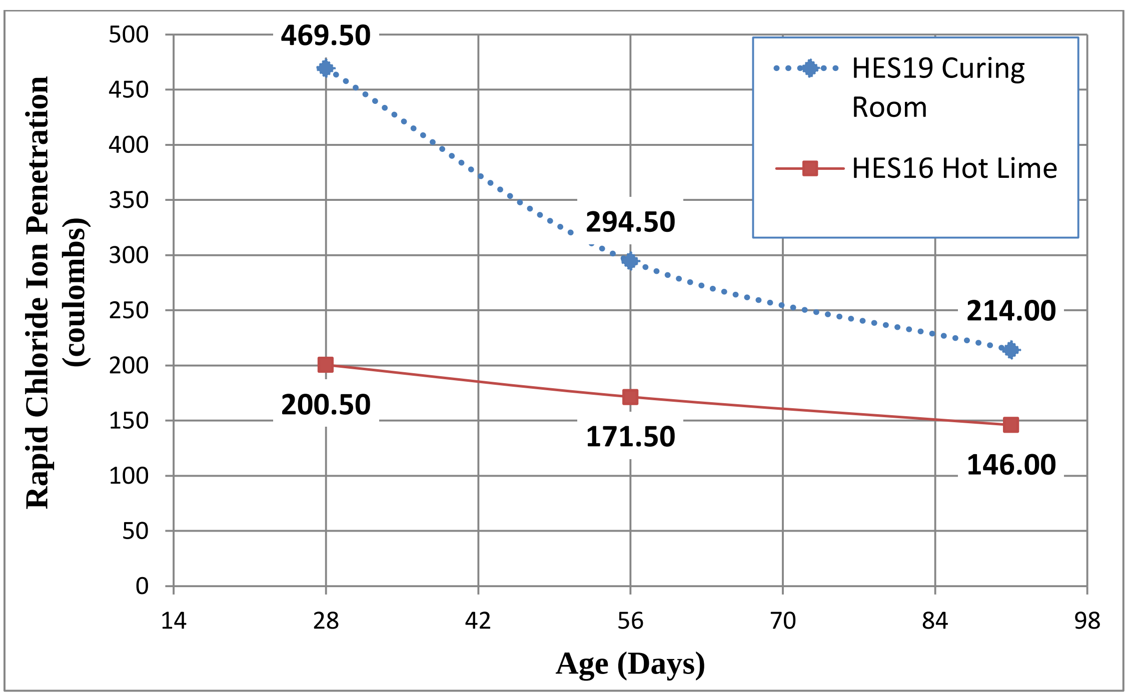

Figure 5.24 RCP versus Age HES mixture

In Figures 5.22, 5.23 and 5.24, the RCP test results of hot curing at 28 days are most comparable to RCP test results of moist curing at 90 days. The percentage difference in HES-HPC between the results of hot cured 28 days and moist curing 90 days is lower. The percentage differences and results are summarized in the following section. The conclusions drawn in the following section are based on the mixtures listed and their specific components.

5.8 Percentage Difference Summary

The percentage differences between results and comparisons in Sections 5.6 and 5.7 are summarized in the following tables.

Table 5.3 Comparison of SR results in hot and cold curing conditions at 28, 56 and 90 days

Surface Resistivity (kohm-cm)			
Mix	28 days Hot Curing	56 days Cold Curing	% Difference
C	25.3	23.30	8.58
SL	78.1	69.80	11.89
7A1	38.44	39.50	-2.69
7A2	37.14	37.86	-1.91
S	67.70	66.6	1.65
CLS	38.50	33.8	13.91
ES	51.80	48.5	6.80

The conclusions that can be drawn from this comparison is that the 28day hot curing and 56 day normal curing results are comparable within 10%. However this conclusion is not applicable to all HPC mixes, it is applicable for mixes with lower or no Fly Ash content. This comparison can be used to predict the 56 day SR moist or lime bath curing results from the 28 day hot curing results. It is necessary to take into account cementitious materials and chemical additives in the mix for such comparisons

Table 5.4 Comparison of RCP results in hot and cold curing conditions at 28 and 90 days

Rapid Chloride Ion Penetration (coulombs)			
Mix	28 days Hot Curing	90 days Cold Curing	% Difference
T	1334.00	1459.00	-8.57
7A1	749.50	916.00	-18.18
7A2	778.00	692.00	12.43
HES16	200.50	214.00	-6.31

The conclusions that can be drawn from this comparison is that the 28day hot curing and 90 day normal curing results are comparable within around 15%. However this conclusion is not applicable to all HPC mixes, and it is mostly applicable for High Early Strength - HPC. This comparison can be used to predict the 90 day RCP moist or lime bath curing results from the 28 day hot curing results.

In Tables 5.5 and 5.6 below, the RCPT and SRT measurements are listed at 56 days for hot and standard curing. The fourth column represents “after how many days of hot curing is the 56 day standard curing measurement achieved.” The mixes without a number of days indicate that the value cannot be determined from the graph.

Table 5.5 Hot and Standard Curing Comparison – RCP

Mix	**56 day Standard Curing RCPT (Coulombs)**	**56 day Hot Curing RCPT (Coulombs)**	**56 day Standard Curing achieved at number of days of Hot Curing**
7A1	1108	434	11 days
7A2	1173	476	9 days
HES	295	171.5	-
ES	1033	876	38 days
T	1748	1052	8 days
PSC	2268	1962	11 days
PSS	628	530	20 days
PSF	1032	610	-
PSFR	2075	1608	-
PSFA	1154	866	-

Table 5.6 Hot and Standard Curing Comparison – SR

Mix	56 day Standard Curing SRT (kohm-cm)	56 day Hot Curing SRT (kohm-cm)	56 day Standard Curing achieved at days of Hot Curing
7A1	39.5	59.1	28 days
7A2	37.9	62.5	28 days
HES	121.0	156.9	13 days
TP53	35.1	61.8	19 days
ES	48.5	56.6	26 days
S	66.3	80.8	26 days
RU	28.6	46.3	13 days
T	21.6	26.3	43 days
PSS	67.8	82.4	18 days
PSF	39.7	71.3	13 days
PSFR	21.5	42.0	14 days
PSFA	33.3	54.6	16 days

5.9 Estimation Factor

The estimation factor determined from the results to obtain the 56 days RCP test results of moist cured samples by multiplying the results of the 28day hot cured samples with a factor. The calculated factor based on the results is 1.48. This estimation factor is applicable to mixes with similar mix designs of the mixes listed below and estimates the results within an average of 10% illustrated in Table 5.7.

The equation for this estimation is the following:

$$\text{56 Days Moist Cured RCP} = \text{28 Days Hot Cured RCP} \times 1.48$$

Table 5.7 Estimation Factor

Mix	Actual 28 days Hot Curing	Actual 56 days Moist Curing	Using Factor 56 days Moist Curing	% Difference
7A1	749.5	1108	1109.26	-0.1
7A2	778	1172.5	1151.44	1.8
HES	200.5	294.5	296.74	-0.8
S	571	728	845.08	-13.9
C	1595	2345	2360.6	-0.7
FA	663	1032	981.24	5.2
ACC	840	1154	1243.2	-7.2

5.10 Comparison of findings with published studies

Researchers, such as Bingol and Tohumcu, concluded that hot curing significantly decrease RCP results and increase SR and Compression test results. (Bingöl & Tohumcu, 2013) Authors also agree that Ground Granulated Blast-furnace Slag significantly increases concrete durability while Fly Ash was not effective in increasing concrete durability. (Teng, et al, 2012) (Bagheri, et al, 2013)

The RCP and SR correlation was developed in the RIME Group NJDOT SRT Project. The RCP and SR correlation was compared with Louisiana Department of Transportation and Development (LADOTD) , Florida Department of Transportation (FDOT) and AASHTO TP 95-11 corelation and surface resistivity evaluation limits. The correlation value in LADOTD report at RCP (28 Day) vs. SR (28 Day) is $R^2 = 0.90$ and $R^2 = 0.92$ from FDOT, while the correlation from RIME is $R^2 = 0.80$. (Rupnow, et al, 2011) Although all three correlations are considered good , however as observed from SR and RCP versus Age graphs , at 28 days some cementitious material did not reach their reaction time which suggests that the correlation is not as accurate at 28 days as at 56 days. The correlation value from LADOTD report data at RCP (56 Day) vs. SR (56 Day) is $R^2 = 0.84$ while the correlation from this study is $R^2 = 0.89$. (Rupnow, et al, 2011)

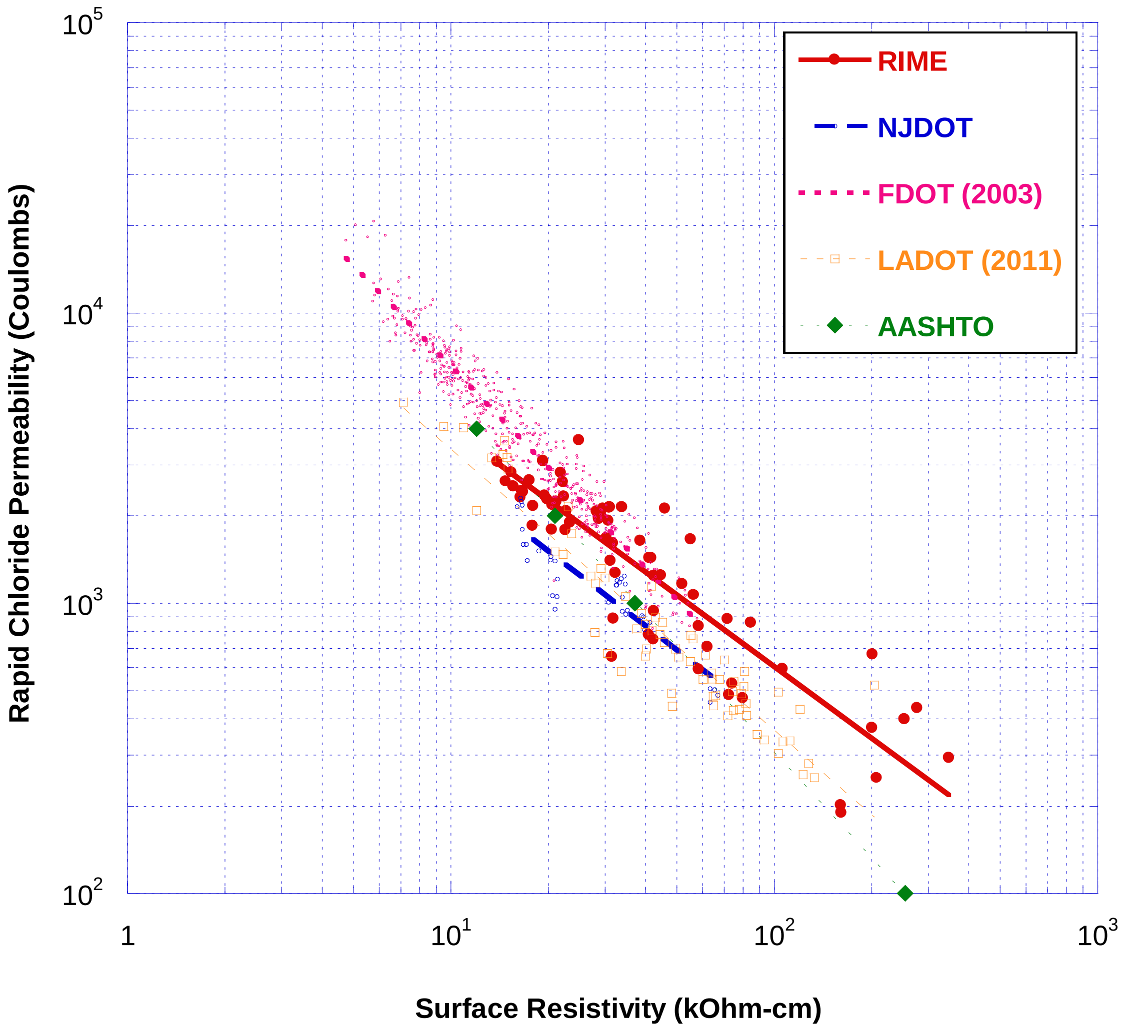

Figure 5.25 Relationship between the Average 28-Day Surface Resistivity and the Average 28-Day Rapid Chloride Permeability Results

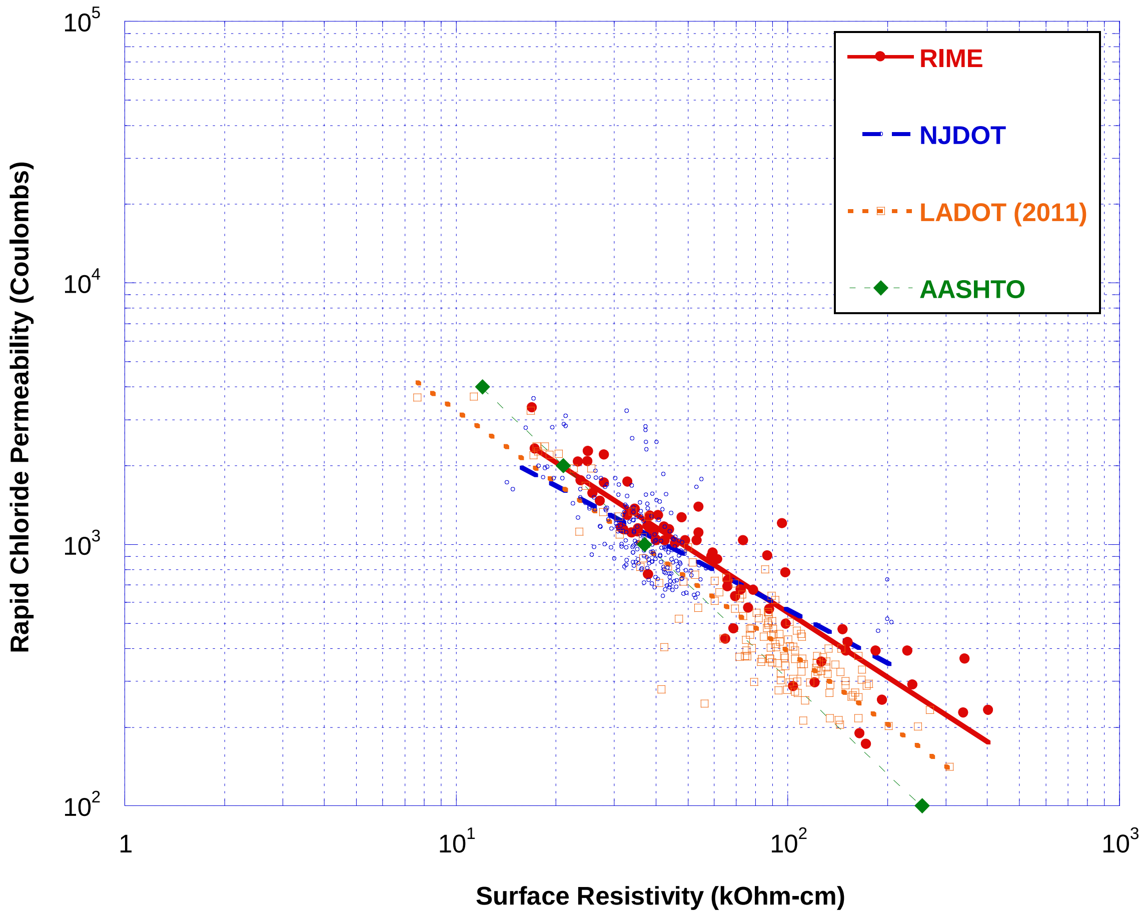

Figure 5.26 Relationship between the average 56-day surface resistivity and the average 56-day rapid chloride permeability results – LADOTD Comparison

Another graph to illustrate and distinguish the similarities and differences in results from FDOT is the graph of test results at 91 days. Correlation comparison between RIME and FDOT Data is shown below in four graphs at 28 days and 91 days. The first graph at each age reflects the entire data taken from FDOT report while in the second draft the FDOT Data with RCP greater than 4000 is excluded. In Figure 5.27 below, it can be concluded that the data points scatter observed at 28 days and 56 days is also observed at 91 days. The RIME data scatter overlaps the scatter from FDOT indicating that some mix designs from all three projects are yielding results within the same range.

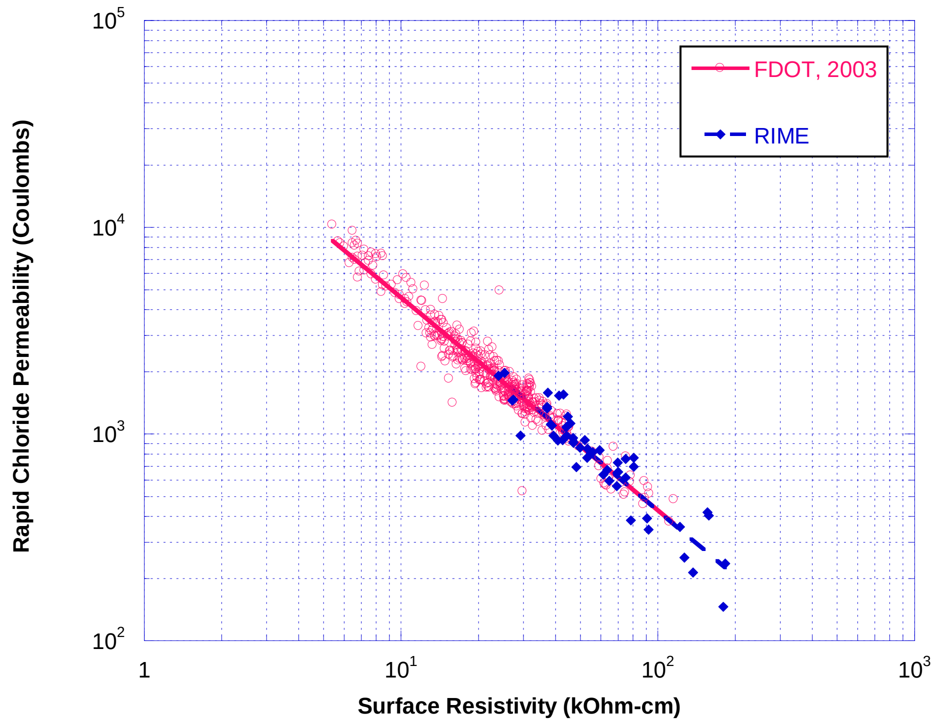

Figure 5.27 Relationship between the Average 91 day Surface Resistivity and the Average 91 day Rapid Chloride Permeability Results

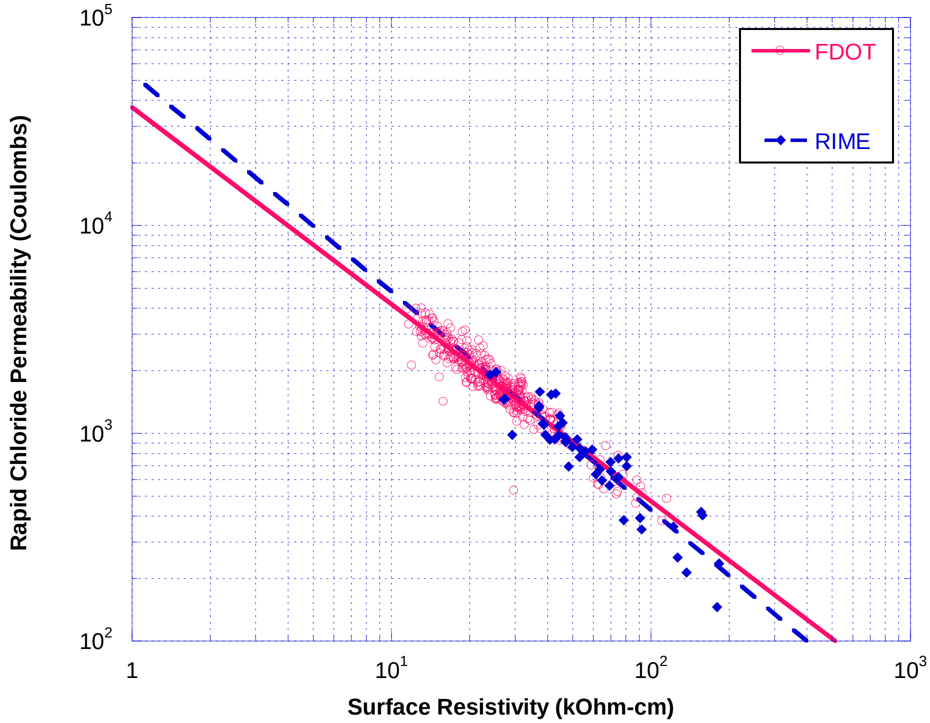

Figure 5.28 Relationship between the Average 91 day SR and the Average 91 day RCP Results (<4000)

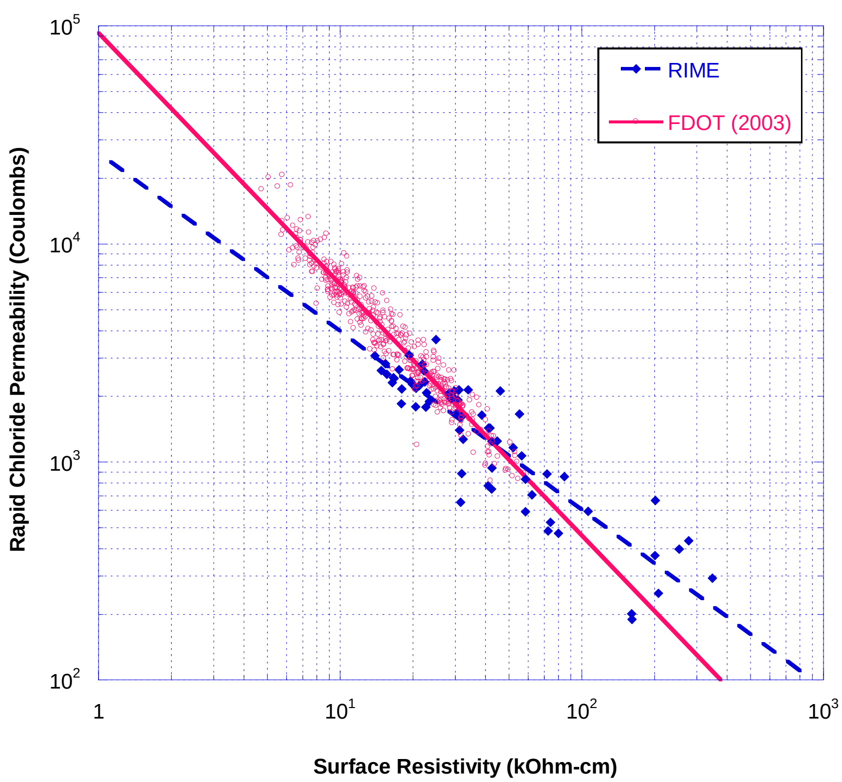

Figure 5.29 Relationship between Average 28 day SR and Average 28 day RCP Results

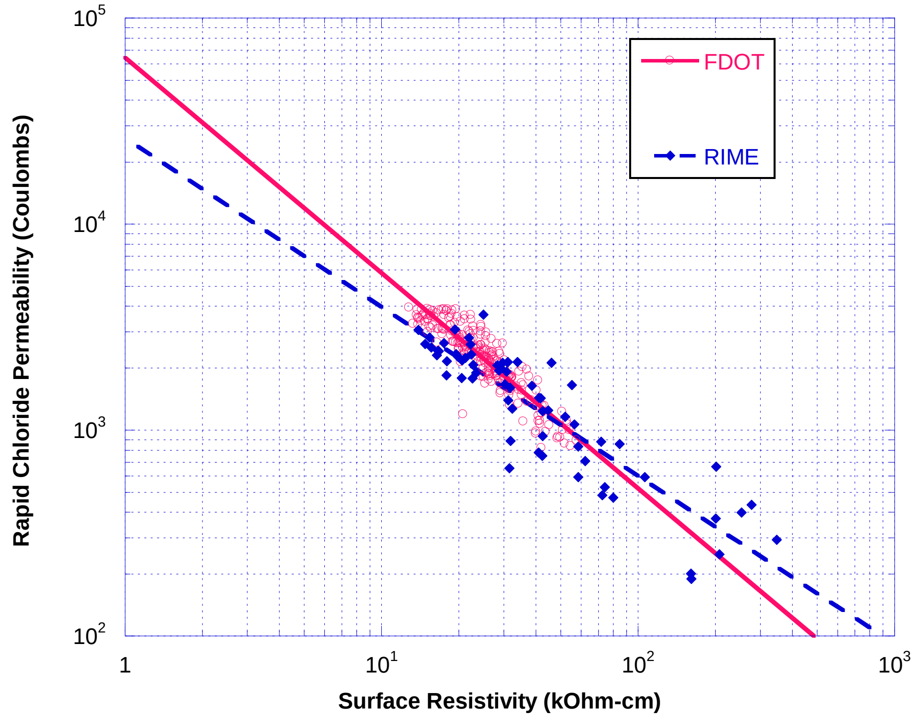

Figure 5.30 Relationship between Average 28 day SR and Average 28 day RCP Results (<4000)

This study includes samples collected from NJDOT and NJTA through RIME Group projects. A correlation comparison is presented below between NJDOT and NJTA Data collected and tested by RIME Group at 56 days. The first graph reflects NJDOT cylinders and the second graph represents NJTA cylinders.

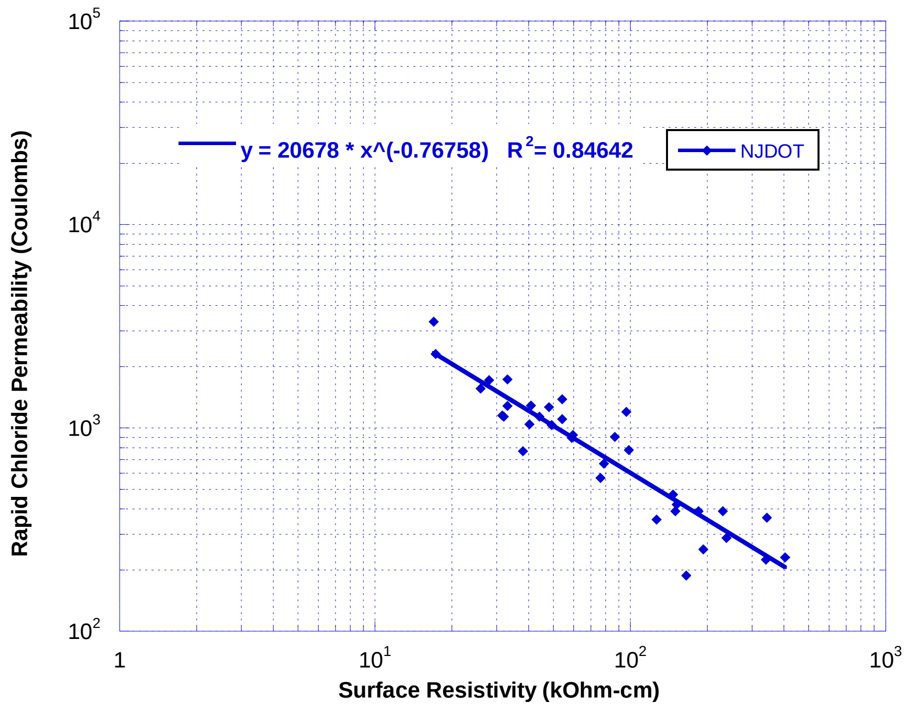

Figure 5.31 Relationship between the Average 56 day SR and the Average 56 day RCP Results-NJDOT

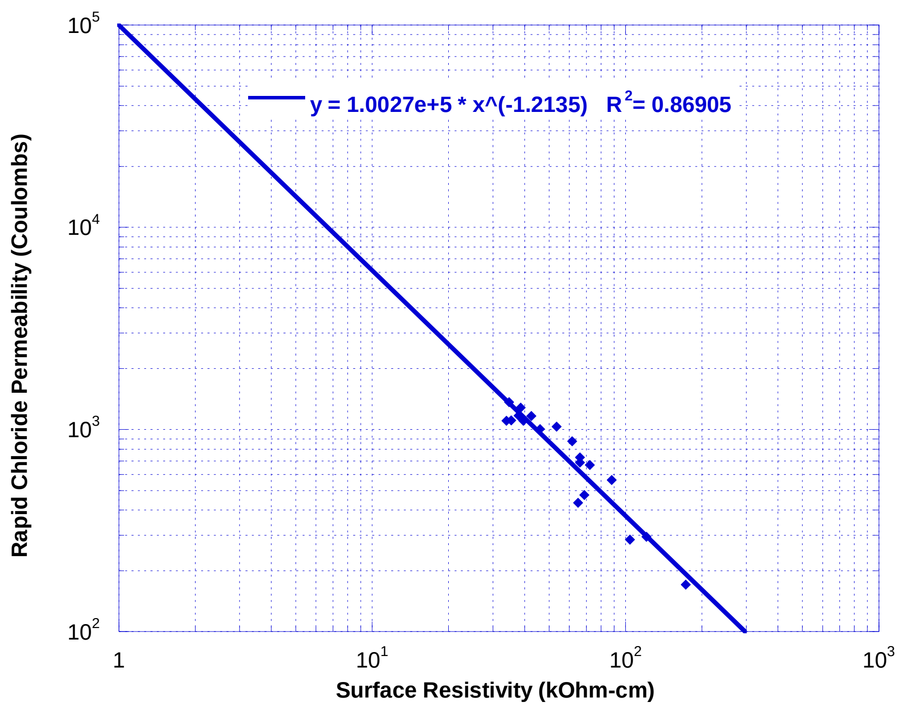

Figure 5.32 Relationship between the Average 56 day SR and the Average 56 day RCP Results-NJTA

5.11 Surface Resistivity Limits

AASHTO TP-95 specifies surface resistivity limits based on correlation of SR and RCP data. Florida Department of Transportation (FDOT) and LADOTD also adopted the AASHTO surface resistivity limits after conducting their studies. Due to many differences such as geographic, temperature, resources and materials, it is necessary that each area develop the surface resistivity limits that accurately evaluate their concrete mixtures.

Surface resistivity limits drawn from the SR vs RCP correlation equations are illustrated in Table 5.8 below. In ASTM C1202 , the RCP limits for low permeability are within 1000 C to 2000 C. Using that low permeability range the low surface resistivity limits can then be calculated using the correlation equations. For the low category, the surface resistivity limits adopted by AASHTO, FDOT and LADOTD are 21 to 37 kohm-cm. The low surface resistivity limits obtained from RIME data is 23 to 45 kohm-cm at 28 days and 23 to 42 kohm-cm at 56 days.

Table 5.8 RIME Data low Surface Resistivity Limits

Correlation graphs	Equation	Surface resistivity limits at RCP (kohm-cm)	
		1000 C	2000 C
RCP 28 days vs SR 28days	$y = 26283x^{-0.82}$ $R^2 = 0.84$	54	23
RCP 56days vs SR 56days	$y = 24048x^{-0.82}$ $R^2 = 0.81$	48	21

Using Data from LADOTD and FDOT report, the correlation was obtained at 28 days and 56 days depending on available data. The comparison between the limits and R^2

values are illustrated in Table 5.9 for 28 days and Table 5.10 for 56 days. FDOT report provides data for 28 days and 91 days of testing.

Table 5.9 Low Surface Resistivity Limit 28 Days (Kohm-cm)

	SR- 28d vs RCP- 28d				
RCPT	**RIME**	**NJDOT**	**FLDOT**	**LADOTD**	**AASHTO**
2000 coulombs	23	14	28	18	21
1000 coulombs	54	33	52	36	37
R^2	0.76	0.77	0.82	0.90	N/A

Table 5.10 Surface resistivity limit 56 days (kohm-cm)

	SR- 56d vs RCP- 56d				
RCPT	**RIME**	**NJDOT**	**FLDOT**	**LADOTD**	**AASHTO**
2000 coulombs	21	15	N/A	18	21
1000 coulombs	48	43	N/A	37	37
R^2	0.81	0.37	N/A	0.84	N/A

CHAPTER VI

6 SUMMARY AND CONCLUSIONS

6.1 SUMMARY

Utilizing proper curing regimes can significantly impact the durability of concrete potentially reduce repairs, traffic interruptions and maintenance costs for bridges. As HPC is categorized based on both strength and durability, curing regimes specification should also be based on strength and durability characteristics. With the excessive use of deicers during harsh winter seasons, chloride ion penetration poses a serious threat to structural integrity. In the past the Rapid Chloride Ion Penetration (RCP) test was correlated with the, well respected, ponding test and has been accepted as the standard. Considering the RCP test drawbacks, the SR test has been introduced and the correlation is being studies, and in some specifications accepted as an alternative.

This thesis presents results of a research project aimed at evaluating the effect of curing regimes on Surface Resistivity (SR) and Rapid Chloride Permeability (RCP) of High Performance Concrete (HPC). A parametric study of five mixes was developed to study the effect of pozzolans, Fly Ash and Slag, and admixtures, Accelerator and Retarder, on concrete cured in several regimes. RCP tests were conducted on 28, 56 and 91 days while SR tests were conducted on 7, 14, 28, 56, 91 days. The curing regimes applied were 100% humidity (moist curing in curing room), saturated $Ca(OH)_2$ solution (lime bath) at 3g of lime per liter of water , and hot (accelerated) saturated $Ca(OH)_2$ solution (hot lime bath) at 100 ± 3°F. Temperature in curing room and lime bath was maintained at 73.5 ± 3.5 °F.

6.2 CONCLUSIONS

Based on the analysis results of this study, the following conclusions can be drawn from the results:

- The effect of different curing regimes, such as moist curing, lime bath curing, and water bath curing was minimal. Difference of SR and RCP measurements between curing conditions was at an average of 3.8 %.
- Hot curing has a significant impact on the SR and RCP measurements. SR testing results increased by up to 218% while RCP test results decreased by up to 75%. Moreover, SRT results of hot cured samples at 28 days were most comparable to regularly cured samples at 56 days, while RCPT results of hot cured samples at 28 days were most comparable to results of standard temperature cured samples at 90 days.
- The addition of slag favorably impacts the surface resistivity of concrete. While the effect of fly ash did not significantly impact SRT and RCPT results in moist and lime bath curing at 14 days, its effect on SRT and RCPT results is evident in hot lime curing. At 28, 56 and 91 days, the surface resistivity of FA mix exceeds that of the control mix. A possible explanation is the slower reaction time of fly ash. As opposed to the significant increase in resistivity reading from 28 days to 56 days, a minimal increase at an average of 8.0 kohm-cm is recorded between 56

days and 91 days. This minor increase in durability suggests that the SCMs have reached, or are very close to reach their reaction time.

- The addition of SCMs (slag and fly ash) to the mixture proportions favorably reduces the rapid chloride penetrability of concrete. While the effect of fly ash did not significantly impact SRT and RCPT results in moist and lime bath curing at 28 days, its effect is evident in hot lime curing. A similar trend can be observed in all three curing conditions; however the rapid chloride permeability of the control mix increased after removal from the hot lime bath and finally decreased at 91 days.
- The addition of the set-accelerating admixture has almost no impact on the surface resistivity of concrete while the mix with the retarding admixture has lower surface resistivity compared to the control mix.
- Similar results and trends are observed for moist curing and lime bath curing; however the trend changes in hot curing where the surface resistivity results decreased at 56 days compared to 28 days and the highest readings obtained at earlier ages were almost achieved at 91 days. The trend observed in hot curing may be attributed to the difference in the concrete hydration process between hot and standard cured specimens.
- Due to materials such as Calcium Nitrite, Calcium Nitrate and Sodium Thiocyanate, the set-accelerating admixture has no effect on the rapid chloride permeability of concrete while the mix with the retarding admixture has higher permeability compared to the control mix.

- For HPC it is proposed to develop the SRT and RCPT correlation for a SR threshold at 56 days due to pozzolanic reaction times.
- The SRT threshold equivalent to an RCPT value of 2000 coulombs for the acceptance criteria for field mixes is very close to limits from other agencies. However, the SRT threshold equivalent to an RCPT value of 1000 coulombs for the acceptance criteria is more conservative. There is a need to perform additional testing of mixes around 1000 coulombs.
- The proposed estimation factor and comparison models can be used to calculate expected moist cured RCP and SR results based on hot cured RCP and SR results for HPC mixtures with similar proportions as listed in Table 3.2.
- Recommended SRT threshold provided by the RIME Group for the NJDOT Specifications based on 56 day RCPT and SRT correlation are shown in Table 6.1 below:

Table 6.1 Recommended SRT Threshold Limits Based on 56 Day RCPT-SRT Correlation

Chloride Ion Penetrability	Surface Resistivity Test 100-mm X 200-mm (4 in. X 8 in.) Cylinder (KOhm-cm) a = 1.5	Surface Resistivity Test 150-mm X 300-mm (6 in. X 12 in.) Cylinder (KOhm-cm) a = 1.5
High	< 9	< 7
Moderate	9 – 20	7 – 16
Low	20 – 48	16 – 38
Very Low	48 – 80	38 – 63
Negligible	> 80	> 63

6.3 SCOPE FOR FUTURE RESEARCH

To broaden our knowledge in the effect of curing regimes on High Performance Concrete durability and specifically on chloride ion penetration, more research may be conducted to optimize the use of curing regimes in enhancing concrete characteristics. Studies on specific combinations of pozzolans and admixtures would assist in identifying the most effective curing procedures for each combination. Due to the different pozzolanic reaction rates of various supplementary cementitious materials, research could be conducted on RCP and SR test past 90 days for more comprehensive observations. The conclusions presented in this study can be amended upon conducting further research with broader scopes and more specific objectives.

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