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Surface Resistivity for Concrete Quality Assurance

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SURFACE RESISTIVITY FOR CONCRETE QUALITY ASSURANCE

By

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Abstract

The goal of this study was to determine the effectiveness of SRT for concrete quality assurance and to evaluate the relationship between SRT and the three chloride ion ingress methods currently used by various State DOTs. Additionally, the influence of binder type and content, concrete age, and water-to cementitious materials ratio on the experimental results were also examined.

In this study, Type V Portland and three SCMs; namely fly ash, slag, and silica fume were used. Fine and coarse, aggregates were supplied by a local quarry. To evaluate the transport properties of the studied concretes, RMT, RCPT, and ACT were employed. The evaluations of experimental results were based on binder content, binder type, w/cm, and concrete age.

The findings of the experimental program revealed improvements in the results of SRT, RCPT, RMT and ACT due to increases in the binder type and content, as well as concrete age. One the other hand, increases in water-to-cementitious materials ratio displayed a reversal trend. Incorporation of the secondary cementitious materials (SCMs), as a partial substitution of Portland cement, improved the results for the four testing methods and the outcomes improved with the increases in the partial replacement of Portland cement with SCMs. Amongst the three utilized SCMs, silica fume produced superior performance in all four testing programs when compared to slag and fly ash. The studied slag concretes produced better results as compared to those of the fly ash mixtures. The statistical evaluations of the test results showed strong inverse relationships between SRT and the three chloride ion penetration methods, substantiating the use of surface resistivity test for concrete quality assurance and paving the way for its adoption by the Nevada Department of Transportation and other public and private agencies.

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Chapter 1 – Introduction and Research Significance

1.1 - Background

Concrete is a material that is vastly utilized in the construction of various structures. The bridges that vehicles drive on, sky scrapers that tower cities, and foundations beneath our feet are all constructed from concrete. Concrete is mainly composed of coarse and fine aggregates, cement, and water. Chemical and mineral admixtures are heavily used in modern concrete to improve various fresh and hardened properties of concrete. One of the main properties that is improved by the usage of mineral admixtures is the transport properties of concrete: the movement of ions into the concrete is referred to its transport properties.

Chloride ion attack is one of the main problems for steel reinforcement in concrete. Overtime external chloride ion can attack the steel by diffusion, permeation, migration, or penetration. Once chloride ion migrates though concrete, it will start to corrode the steel which can lead to the eventual deterioration and failure of both concrete and steel reinforcement. Therefore, it is imperative to evaluate the resistance of concrete, with or without mineral admixtures, to chloride ion penetration using accelerated methods such as rapid chloride penetration test (RCPT), rapid migration test (RMT), and accelerated corrosion test (ACT). It is equally important to understand how surface resistivity relates to the above-mentioned transport properties.

The main goals of this study were to examine the influence of binder types, water-to-binder ratio, and age on concrete surface resistivity and transport properties. Additionally, this study aimed to investigate the extent to which surface resistivity can be correlated to the results of rapid chloride penetration, rapid migration, and accelerated corrosion tests.

1.2 History of Concrete Surface Resistivity

The four pin Wenner array did not start out initially as a method to evaluate surface resistivity of concrete. The Wenner array was first published in the National Bureau of Standards, the predecessor of the National Institute of Standards and Technology (NIST) by Frank Wenner in 1915 to test soil. The mechanism of the Wenner array today is still the same as the array when the four-pin array was first conceived by Frank Wenner over 100 years ago. Even though Frank Wenner designed the probe to measure soil resistivity, the device was slowly used for surface resistivity of concrete. Today's Wenner probe is a device that has four probes, the two outer probes will emit an alternating current (I), the two inner probes will measure the potential difference (V), and the spacing (a) between each probe is known. According to the Proceq instructions manual for their resistivity meter, the resistivity can be calculated by using Equation 1.1.

$$\rho = 2\pi aV/I \text{ (k}\Omega\text{-cm)} \qquad \text{(Equation 1.1)}$$

The Wenner probe is much faster and cheaper than the traditional methods used to test transport property of concrete. As such, a number of State Departments of Transportation (DOT) explored the use of surface resistivity test as a viable alternative to RCPT. The Florida DOT (FDOT) was first to study the possible correlation between SRT and RCPT. As the readings in SRT increased the RCPT readings decreased and vice versa. The inversely proportional relationship was the same for both 28- and 91-days cured samples. Following the FDOT study in 2003, many other state DOTs followed suite, and began to conduct studies of their own to evaluate relationships between SRT and RCPT. The basis of the study for many State Departments of Transportation was to determine the relationship between the results of the surface resistivity and rapid chloride penetration tests. Additionally, many DOTs incorporated supplementary cementitious material (SCM) into their mixtures to simulate the actual mixtures used in the field, and thus investigated their influence on the results of concrete surface resistivity and rapid chloride ions penetration test.

The higher the measurement from a Wenner probe means the material is more capable in resisting the flow of ions. Although, surface resistivity indicates the ability of a material to resist the flow ion, there isn't actually a way to know if corrosion is occurring. The Wenner probe only gives out readings, but the only way to actually detect and examine corrosion is to physically break open concrete specimens.

Before the resistivity meter can be used, the probes must be saturated with water, so the probes can better emit the current and measure the voltage. The Proceq instruction manual recommends saturating the probes by pressing the probes into a shallow bucket of water.

Generally speaking, surface resistivity test indicates material susceptibility to the flow of an electric current or flow of ions. The chart shown in Table 1.1 presents a typical inverse relationship between RCPT and SRT. It can be seen that as reading for surface resistivity reduces, the higher value RCPT readings should be expected.

Table 1. 1: Surface Resistivity Readings for 4"x8" and 6"x12" Compared to RCPT Measurements (Gudimettla and Crawford, 2015)

Chloride Ion Penetration	Charges Passed (Coulombs)	4"x8" Cylinder (KOhm-cm)	6"x12" Cylinder (KOhm-cm)
High	>4,000	<12	<9.5
Moderate	2,000-4,000	12-21	9.5-16.5
Low	1,000-2,000	21-37	16.5-29
Very Low	100-1,000	37-254	29-199
Negligible	<100	>254	>199

1.3 Advantages and Disadvantages of Surface Resistivity

Surface resistivity is very advantageous when it comes to saving time and operation costs. Unlike RCPT which takes six hours to complete, and before then an additional 24 hours for the desiccation process, the SRT can be performed on samples taken straight out of curing room. The Wenner probe can also be used in the field to evaluate concrete surface resistivity. The Wenner probe gives immediate results because once the probe is pushed in, the resistivity reading is displayed on the screen of the probe. The probe can also be used on multiple samples, so one probe can test numerous samples using both laboratory and field concrete.

On the other hand, RCPT is a much more expensive test because one cell can only test one sample at a time. Multiple cells will be needed to measure different batches of concrete. Software is needed to collect the data during the 6-hour testing period, and a RCPT laboratory test device is needed to connect the RCPT cells to measure the resistance of concrete against chloride penetration. Additionally, RCPT device can only be used in a laboratory setting because it's very difficult to bring all the necessary equipment to the field. According to the Federal Highway Administration (FHWA) website, the SRT can save contractors $1.5 million annually in quality control costs. As shown in Table 1.2 LaDOTD saved approximately $101,000 in personnel costs in its first year after implementing the SRT.

Table 1. 2: LaDOTD cost comparison annually between SRT and RCPT (Rupnow and Icenogle, 2012)

Test Method	Number of Lots	Number of Testing Hours Required	Technician Hourly Wage ($)	Tech. Cost ($)	Total Cost ($)	Cost Per Lot ($)
ASTM C 1202	480	3840	23.38	89,779.20	107,779.20	224.54
Surface Resistivity	480	158.4	23.38	3,703.39	6,503.39	13.55
				Savings	101,275.81	

When SRT is compared to RMT, there is a similar advantage of SRT is to RCPT. The SRT has a significantly shorter testing period than RMT as the latter takes 24 hours to complete in addition to the one day of desiccation prior to the actual test. Once RMT testing is completed, it has to be broken apart and the amount of chloride penetration has to be manually measured. In total, RMT takes a full two days to complete. RMT measurements is more prone to errors than

RCPT and SRT because the amount of chloride penetration has to be measured manually. When RMT is compared to RCPT, RCPT is a more consistent testing method since it is automated. In comparison, to add up, SRT takes just a few minutes to complete as compared to two days for both the RCPT and RMT. Accelerated corrosion is also another test that was implemented in this study. Unlike RCPT and RMT, the accelerated corrosion test doesn't measure the chloride ion penetration. Accelerated corrosion measures the amount of time for a concrete sample to fail. The amount of time it takes for an accelerated corrosion test sample to fail is difficult to predict. Samples can fail within a few weeks or can take months from the initial date of testing.

However, there are some concerns when dealing with the surface resistivity test. The SRT's Wenner probe is a very sensitive device, so any subtle movements can cause a misreading. It takes a steady hand to properly conduct the test. Another concern with the SRT is that all pins of the probe must be finally in contact with the surface of concrete in order for the device to display correct readings. Indeed, small imperfections on the surface of the concrete can cause improper surface resistivity readings. In addition, in order for multiple measurements to be consistent, the device needs to be placed at the exact spot on the concrete surface every time.

1.4 Concrete Chloride Ingress

Concrete is used for buildings, dams, towering sky scrapers, and even the canals that connects water ways. While concrete can be used to build structures that can last for centuries, it is not as an impenetrable material as it is perceived. A big problem that could impact concrete and particularly reinforcements is the penetration of chemical ions inside concrete. Transport mechanisms that causes ions to move through the concrete are diffusion, capillary action, permeability, migration, and adsorption. Transport properties are impacted by many factors such as water to cement ratio (w/cm), cement content, pore structure, and supplementary cementitious material.

1.4.1 Diffusion

Diffusion occurs when there is a higher concentration of free ions in a pore solution, and the flow travels from the higher concentration to the areas of lower centration (Cement Concrete & Aggregates Australia, 2009). For this mode of transportation to occur, the specimen must be fully saturated, thus concrete structures has to be submerged in order for diffusion to occur. The reason for the movement of ions from higher to lower concentration is to reach equilibrium in concentration. Chloride ion penetration in concrete structures is caused mainly by sea water, and in the laboratory, samples can be subjected to the same type of environment as concrete is submerged in seawater. With no electrical current, and concrete is a fully saturated condition, diffusion is the main mode of transportation for ions (Mutale, 2014). Figure 1.1 shows the movement of ions through concrete through diffusion.

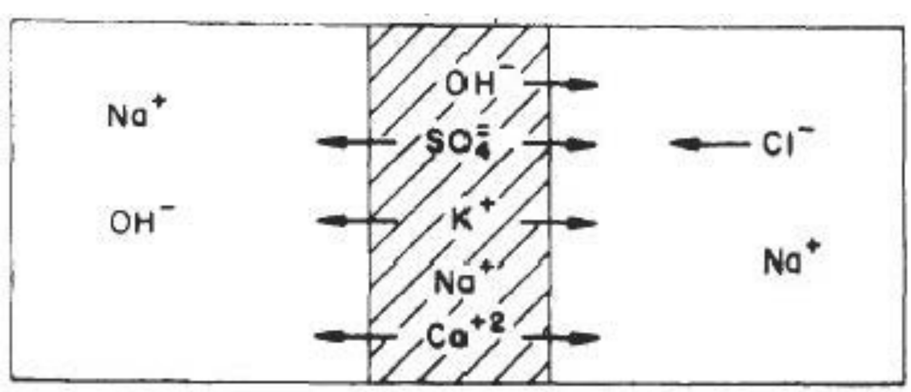

Figure 1. 1: Diffusion of ions through concrete (Andrade, 1993)

1.4.2 Capillary Action

There are two forms of capillary action which are capillary absorption and capillary suction. Capillary absorption is influenced by density, viscosity, surface tension, pore structure, and surface energy of the concrete (Cement Concrete & Aggregates Australia, 2009). Water movement weaves around spaces of a porous material affected by the above-mentioned variables. Instead of the movement of ions in the case of diffusion, capillary action is the movement of the liquid itself. It’s the movement of liquid in the spaces that moves the chloride ions along with it. Capillary suction is the other mode of capillary action. Capillary suctions occur when one side of a concrete member is in contact with water to allow for capillary suction to occur (Cement Concrete & Aggregates Australia, 2009).

1.4.3 Permeability

Permeability is caused by a pressure head and it causes gases or liquids to flow through a porous material. Structures that are exposed to liquid under a pressure head will experience this type of chloride movement. Permeability of concrete is impacted by the pore structure of the concrete and the viscosity of the liquid. If there is a low amount of pore structure, the liquid will have difficulty to move through concrete, and if the liquid is too viscous, it also has a difficult time flowing through concrete while carrying chloride ions (Cement Concrete & Aggregates Australia, 2009). Concrete structures that can experience permeation are liquid containing structures or basement exterior walls.

1.4.4 Migration

The migration mode of ion movement is caused by an electrical field. Electrical field will cause ions of positive or negative to charge to move to electrodes of the opposite charge. Migration can occur if there is a current that is emitted from a frayed wire or from concrete rehabilitation techniques (Cement Concrete & Aggregates Australia, 2009). ASTM C1202 and ASSHTO T277 are the tests that are commonly used to measure chloride ion migration. ASTM C1202 and ASSHTO T277 are used by multiple state DOTs in testing concrete as means of quality control. The tests measure the amount of electoral current that passes, in coulombs, through a 2-inch-thick sample in a 6-hour period. Figure 1.2 shows the migration of ions through concrete.

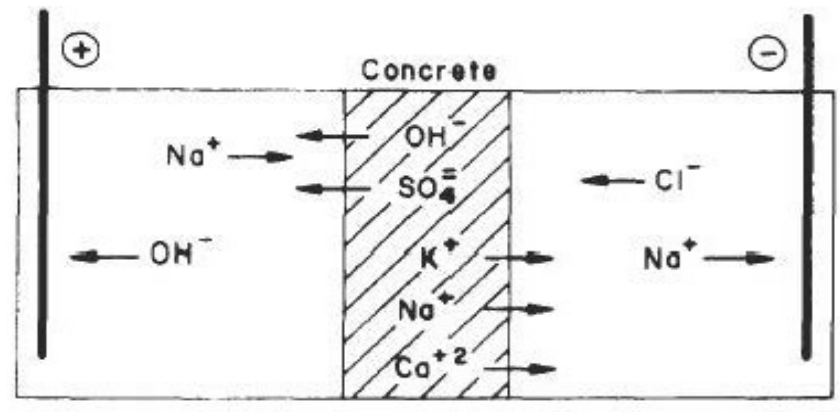

Figure 1. 2: Migration of ions through concrete (Andrade, 1993)

1.5 Past Studies on Surface Resistivity of Concrete

The objective of this section is to provide information on past studies that were reported regarding the comparison between RCPT and SRT results, the impacts of supplementary cementitious material on concrete surface resistivity, and relationship between surface resistivity and chloride ingress in concrete. The major findings and conclusions made from the studies are summarized in Table 1.3 (A, B, C, and D). The summarized information from the previous studies provides a better understanding on what was already done regarding SRT and RCPT, and the studies that are that needed to better understand the correlation between concrete surface resistivity and its transport properties.

Table 1. 3A: Summary and subject of previous studies on RCPT and SRT and the impact of supplementary cementitious material on surface resistivity readings

Author/Authors, Year	Subject of study	Major Findings of Study
Liu et al., N/A	Various resistivity meters from different manufacturers and models were not comparable. If the resistivity readings were converted to bulk resistivity values, then surface resistivity from different manufacturers and models can be compared.	If the following factors were taken into account such as electrode spacing, degree of saturation, and temperature, the surface resistivity readings from different models and manufacturers can be converted to bulk resistivity values. The converted bulk resistivity values were comparable to one another.

Table 1. 3B: Summary and subject of previous studies on RCPT and SRT and the impact of supplementary cementitious material on surface resistivity readings

Author/Authors, Year	Subject of study	Major Findings of Study
Jenkins, 2015	Comparison of SRT to RCPT and the Volume of Permeable Voids method (ASTM C642) using KDOT mixtures.	Surface resistivity 28-day tests can substitute 56-day RCPT. SRT was compared to ASTM C642 test, but there was no strong correlation between SRT and ASTM C642 test.
Layssi et al., 2005	Compared both bulk resistivity and surface resistivity to RCPT, also determined the factors that influenced both resistivity and RCPT measurements.	The 4-point Wenner probe provided consistent data. There was a nonlinear relation between electrical resistivity and RCPT if there was a temperature change, and variations in the pore solution used during RCPT. A linear relationship could occur if there is no temperature change in the samples and a consistent pore solution.
Rupnow & Icenogle, 2012	Investigated the use of surface resistivity as a means of quality assurance.	Surface resistivity measurements correlated with rapid chloride permeability measurements for a wide range of samples. Measurements correlated well for 14, 28, and 56-day specimens. The standard deviation for surface resistivity was less than 3kΩ-cm, but RCPT measurements ranged from 300-500 coulombs.
Smith, 2006	Tried to correlate SRT and RCPT and also used electrical techniques to predict the diffusion coefficient of concrete.	Steel did influence resistivity readings if the depth of the cover is less than the inter-point spacing on the Wenner probe. If the probe is placed perpendicularly along the reinforcing steel the measurements will not be as impacted heavily. There was a weak relationship between surface resistivity and rate of chloride diffusion of saturated concrete.

Table 1. 3C: Summary and subject of previous studies on RCPT and SRT and the impact of supplementary cementitious material on surface resistivity readings

Author/Authors, Year	Subject of study	Major Findings of Study
Jenkins, 2015	Comparison of SRT to RCPT and the Volume of Permeable Voids method (ASTM C642) using KDOT mixtures.	Surface resistivity 28-day tests can substitute 56-day RCPT. SRT was compared to ASTM C642 test, but there was no strong correlation between SRT and ASTM C642 test.
Smith, 2006	Tried to correlate SRT and RCPT and also used electrical techniques to predict the diffusion coefficient of concrete.	Steel did influence resistivity readings if the depth of the cover is less than the inter-point spacing on the Wenner probe. If the probe is placed perpendicularly along the reinforcing steel the measurements will not be as impacted heavily. There was a weak relationship between surface resistivity and rate of chloride diffusion of saturated concrete.
Eagan, 2015	How Class F or Class C fly ash, ground granulated blast furnace slag, silica fume, and metakaolin impacted the measurement of the resistivity meter.	A combination of slag and metakaolin gave a very large reading for SR. It meant that a particular mixture would be very good in protecting concrete against chloride ion attack. A combination of SCMs performed the best, when compared to if only one type of SCM was used in the mix.
Mutale, 2014	A study and comparison between SRT, salt ponding, bulk diffusion, RMT, and RCPT.	Surface resistivity sensitive to the outside elements. The author recommends conducting the SRT in laboratory conditions. In laboratory condition lessened the impact of temperature and moisture on concrete. In blended cement the water binder ratio has a greater impact on surface resistivity compared to slag and fly ash.
Shaikhon, 2015	The impact of sulfate and chloride ions on concrete resistivity.	Both SR and bulk resistivity (BR) resistivity measurements decreased with increased chloride penetration. It was the opposite for sulfate ions because as the sulfate ion penetration increased so did the BR and SR readings.

Table 1. 3D: Summary and subject of previous studies on RCPT and SRT and the impact of supplementary cementitious material on surface resistivity readings

Author/Authors, Year	Subject of study	Major Findings of Study
Shahroodi, 2010	Compared the SRT to RCPT as a possibility of replacement. ASTM C1585, BR, initial and secondary water sorptivity also used in the experiment.	The lower the moisture content and w/cm caused a higher SR reading.
Nassif et al., 2015	Investigated the use of surface resistivity as a means of quality assurance in the state of New Jersey.	Hot curing changed the results of both SRT and RCPT. SRT readings increased up to 218% and RCPT measurements decreased up to 75% because of hot curing. At the 28, 56, and 91-day intervals fly ash results were higher than the control mixes. Fly ash and slag aided in reducing the amount of chloride penetration.
Chini et al., 2003	Investigated the use of surface resistivity as a means of quality assurance in the state of Florida.	Silica fume performed the best out of three cementitious material used the study the SRT. It reduced the amount of ion penetration the most. It was followed then by blast furnace slag and fly ash. Neither the w/cm and type of coarse aggregate had a consistent effect on SRT and RCPT.
Kevern et al., 2015	Compared the SRT test to RCPT, chloride ion diffusion of MoDOT concrete mixtures. Use of SRT to replace RCPT because it saved time and expenses.	SRT was useful for mixture development and acceptance, but SRT for field bridge deck needed to be tested further. SRT on asphalt emulsions was also accurate. Like previous studies between SRT and RCPT, the MoDOT study showed a good correlation between the two tests.
Ryan, 2011	A study that compared RCPT and SRT for Tennessee DOT (TDOT) specific mixes.	SRT was a suitable replacement to RCPT and was recommended as the "gold standard" in measuring the chloride penetration is the ponding test (ASTM C1543). Unlike RCPT the ponding test takes many months to be completed, that isn't practical for DOTs or inspection contractors to use.

1.6 Impact of Supplementary Cementitious Materials on Surface Resistivity

Supplementary cementitious materials (SCMs) are used to improve either fresh or hardened concrete properties. SCMs can either replace a portion of cement or can be added as an addition to concrete, or as a secondary cementitious material to replace a portion of fine aggregate. Fly ash, ground granulated blast furnace slag, and silica fume are typically used. Chloride ion ingress into concrete should be impeded if SCMs are added into concrete. In this study the SCMs were added to substitute a portion cement. No SCMs were blended together.

1.7 Research Objective and Thesis Outline

Concrete is one the most widely used construction materials on the planet. The massive dams that hold back lakes and rivers, and the massive skyscrapers that tower cities are made from concrete. While concrete may seem to be impenetrable, and capable to handle massive amount of loads and heat, it is also very susceptible to chemical attack. Sulfides and chlorides can attack concrete from multiple internal and external sources. A major problem associated with chemical attack is that it leads to the eventual corrosion of the reinforcing bars embedded inside concrete. A number of testing programs has been developed as a way to measure and quantify the concrete resistance to chloride and sulfide ingress. As for this study, rapid chloride permeability test (RCPT), rapid chloride migration test (RMT), and the accelerated corrosion test (ACT) were used to examine the ability of concrete to resist chloride penetration.

The main objectives of this study were:

- To report on past studies on concrete surface resistivity and the current chloride penetration testing methods.
- To understand the impacts of binder type, water-to-binder ratio, and concrete age on the results of, RCPT, RMT, SRT, and ACT.

- To determine viable correlations between SR and RCPT, SRT and RMT, and SRT and ACT.

In order to achieve the stated objectives, the findings of this study are presented in the following five chapters.

Chapter one reviews past studies on SRT and the reported relationship between SRT and RCPT. In addition, history of concrete surface resistivity and chloride ingress methods are presented:

Chapter two deals with the experimental program of the study. The chemical and physical characteristics of raw materials, mixtures constituents and proportions, mixing procedures, and the utilized testing methodologies are described.

Chapter three presents the results and discussion of the research study. The findings obtained from the employed testing methods as functions of binder content, water-to cementitious materials ratio, and concrete age are presented and discussed.

Chapter four reports on the relationship between the results of SRT and RCPT, SRT and RMT, and SRT and ACT. In addition, factors influencing the results of this testing methods along with their statistical relevancies are presented.

Chapter five presents the conclusions of the study.

1.8 Research Significance

Due to the amount of time saved when compared to RCPT, and the non-destructive nature of the test, the SRT has captured the attention of several DOTs to conduct studies of their own to find relationships between RCPT and SRT. This study aims to provide a better understanding of the relationship between the results of SRT, RCPT, RMT, and ACT. Additionally, this study provides a valuable insight into the impact of binder content and type, concrete age, and w/cm on the findings of the above-mentioned testing methodologies. It is hoped that the outcome of this study provides an opportunity for the concrete surface resistivity test to be more widely adopted for concrete quality assurance. Furthermore, implementation of the SRT decreases the time needed to analyze concrete samples for its susceptibility to chloride ion penetration. The time saved allows for the public and private entities to allocate their resources elsewhere.

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Chapter 2 - Materials and Testing Program

2.1 Materials

The materials used in this study were taken special care to ensure consistency for the studied mixtures. All materials used in the study had to be stored inside the laboratory at least a day prior to the day of batching. The adopted procedure allowed for the materials to reach room temperature 21 ± 2°C (70 ± 3°F). The utilized aggregates had to be properly dried and graded before use. This chapter deals with material characteristics, mixture constituents and proportions, mixing procedure, and testing methods used to evaluate RPCT, RMT, ACT, and SRT of the studied concretes.

2.1.1 Aggregates

The shape and size of the coarse aggregate play a vital role in various properties of concrete such as strength, workability, volume, stability, and durability. In general, rounded shaped aggregate allows for the concrete to fill in voids better than non-rounded and flat shaped aggregate. Size distribution of fine and coarse aggregate are important to have a concrete mixture with the least number of entrapped voids.

The fine and coarse aggregate used in this study was provided by a local quarry in Southern Nevada. The coarse aggregate and fine aggregate were both delivered in super sacks. The coarse aggregates were manually graded before they were stored in 55-gallon metal drums. The coarse aggregates were graded into four distinct sizes: (1) retained on 19 mm (3/4 in) US. sieve, (2) retained on 13 mm (1/2 in) US sieve, (3) retained on 10 mm (3/8 in) US sieve, and (4) retained on #4 US sieve. All barrels were lined inside with a plastic liner to prevent any moisture entry. The coarse aggregates conformed with the ASTM C33 size designation 7 and 67, and the fine aggregate were in accordance to ASTM C33 as well. The fine aggregate was dried in the outdoor horse troughs before use. Periodically, the horse troughs were moved inside the laboratory and a fan was used to dry the fine aggregate whenever weather was not accommodative. Both fine and coarse aggregates were stored in the laboratory a day prior to batching. Table 2.1 shows the size distribution of the fine aggregate, whereas Table 2.2 shows the various physical properties of the fine aggregate used in the study.

Table 2. 1: Gradation of Fine Aggregate

Sieve Number	Percent Passing	Allowable Range
3/4 in	100	100
#4	100	95 to 100
#8	95	80 to 100
#16	65	50 to 85
#30	43	25 to 60
#50	24	5 to 30
#100	9	0 to 10
#200	2.7	0 to 3

Table 2. 2: Absorption and Specific Gravity of Fine Aggregate (Moradi, 2014)

Relative Density (Specific Gravity) Oven-Dry	2.755
Relative Density (Specific Gravity) Saturated-Surface Dry	2.777
Apparent Relative Density (Apparent Specific Gravity)	2.818
Absorption (%)	0.81
Damp Loose Unit Weight ASTM C29	85 pcf@1.5% moisture

2.1.2 Portland Cement

Portland cement is a pivotal ingredient in concrete, and it's one of the most critical ingredients. The Type V Portland cement used in this study complied with the ASTM C150. Type V Portland cement known for its high resistance to sulfate attack, and it is mandatory for concrete construction in Nevada due to the high concentration of salts in the soil. The Type V cement was delivered in 55-gallon plastic lined metal containers. The night prior to batching, cement was transferred from the 55-gallon drums to 5-gallon plastic lined buckets. The cement was stored inside the laboratory at a temperature of 21 ± 2°C (70 ± 3°F). Tables 2.3 and 2.4 describes the physical and chemical analyses of the Portland cement.

Table 2. 3: Physical Analysis of Portland Cement

Item	ASTM Test Method	Results	Specifications
Air Content (%)	C185	6	12 Max
Fineness (cm^2/g)	C204	4280	2600 Min
Autoclave Expansion	C151	0	0.80 Max
Compressive Strength (psi)			
1 Day	C109	2450	NA
3 Day	C109	4340	1160 Min
7 Day	C109	5330	2180 Min
28 Day	C109	6570	3050 Min

Table 2. 4: Chemical Analysis of Portland Cement

Compound	Results (%)	Type V Specification
CaO	65.7	NA
SIO_2	21.1	NA
Al_2O_3	4	NA
Fe_2O_3	3.7	NA
MgO	1.2	6 Max
SO_3	3.1	2.3 Max
Loss on Ignition	2.4	3.5 Max
Insoluble Residue	0.68	1.5 Max
Alkalis (%Na_2O+0.658 K_2O)	0.44	0.6 Max
CO_2	1.5	NA
$CaCO_3$ (In Cement)	3.7	5 Max
$CaCO_3$ (In Limestone)	94	70 Min

2.1.3 Fly Ash

Fly ash is commonly used as a secondary cementitious material in concrete. It is a by-product of burning coal in power generating plants. Due to the availability of coal in many countries, fly ash is widely utilized in concrete to replace a portion of Portland cement in order to improve its fresh and hardened properties. There are two types of industrial fly ash: Class C and Class F. Class F fly ash is a result of burning bituminous and subbituminous coals that can be found in power plants east of the Mississippi River (Mindess, Young, Darwin, 2003). Class C fly ash, which is generated from burning lignite coals, is more prevalent in States to the west of the Mississippi River (Mindess, Young, Darwin, 2003). Fly ash greatly improves workability of concrete. The improvement of workability results in a decrease of required mixing water, thus increases in overall strength and resistance to chloride and sulfate ions ingress. The fly ash used in the study was delivered in plastic lined 55-gallon barrels. It was then transferred into 5-gallon buckets and stored inside the laboratory at a temperature of 21 ± 2°C (70 ± 3°F). Table 2.5 (A and B) shows the physical and chemical properties of the fly ash.

Table 2. 5A: Chemical and Physical Properties of Fly Ash (Moradi, 2014)

Chemical Compositions		ASTM/AASHTO LIMTS		ASTM Test Method
		Class F	Class C	
Silicon Dioxide	59.93			
Aluminum Oxide	22.22			
Iron Oxide	5.16			
Total Constituents	87.31	70% min	50% min	D4326
Sulfur Trioxide	0.38	5% max	5% max	D4326
Calcium Oxide	4.67			
Moisture	0.04	3% max	3% max	C311
Loss of Ignition	0.32	6% max	6% max	AASHTO M295
		5% max	5% max	
Total Alkalies, as Na_2O	1.29	Not Required		C311
When required by purchaser		1.5 max	1.5 max	AASHTO M295

Table 2. 5B: Chemical and Physical Properties of Fly Ash (Moradi, 2014)

Chemical Compositions		ASTM/AASHTO LIMTS		ASTM Test Method
		Class F	Class C	
Physical Properties				
Fineness, % Retained on #35	18.08	34% max	34 max	C311, C430
Strength Activity Indeix-7 or 28 Day Requirement				C311, C109
7 day, % of Control	83	75% min	75% min	
28 day, % of Control	79	75% min	75% min	
Water Requirement, % Content	97	105% max	105% max	
Autoclave Soundness	-0.02	0.8% max	0.8% max	C311, C151
Density	2.31			C604

2.1.4 Granulated Blast Furnace Slag

Blast furnace slag is another industrial by-product that improves concrete properties. Slag is a by-product of the production of steel. Blast furnace slag is mainly composed of lime, alumina, silica, and iron. To form slag, the molten slag from the steel production or refinement process must be quickly cooled to form a hydraulically active calcium aluminosilicate glass (Mindess, Young, Darwin, 2003). If the molten slag is cooled slowly, its crystalized form will be inert, hence not usable as a supplementary cementitious material. Slag reduces workability of concrete, so there will be a need to either increase the water to cement ratio or add a water reducer (WR) or high-range water reducer (HRWR) to improve concrete workability. Table 2.6 and 2.7 shows the chemical composition and mechanical/physical properties of the utilized slag.

Table 2. 6: Chemical Composition of Slag (Najimi, 2016)

Compound, %	Slag
Calcium Oxide	43.64
Silica	31.0
Alumina	11.5
Iron Oxide	0.8
Magnesium Oxide	4.7
Potassium Oxide	0.84
Sulfur Trioxide	4.85
Titanium Oxide	0.57

Table 2. 7: Physical and Mechanical Properties of Slag (Najimi, 2016)

Property	Allowable Limit per ASTM C989	Slag Results
7 day compressive strength (MPa)	75 min	90
28 day compressive strength (MPa)	95 min	107
Air content of mortar (%)	12 max	5.8
Specific Gravity (g/cm^3)		2.87
Loss on Ignition (%)	10 max	0.3
Autoclave Expansion (%)	0.5 max	0
Specific surface cm^2/g		5420
Remaining on #325 sieve (%)	20 max	2.6
Sulfide Sulfur, % as SO_3	2.5 max	0.66
Sulfate Ion, % as SO_3	4 max	3.2

2.1.5 Silica Fume

Silica fume is a very fine material, finer than Portland cement, and a by-product from the production of aluminum or from the production of metals containing silicone. Like other SCMs, silica fume helps to improve certain properties of concrete. It is a very fine amorphous material, and because of its high surface area it reduces workability of concrete significantly, thus requiring large amount of a water reducer to maintain the needed water-to-cementitious materials ratio and workability. The fineness of the silica fume particles allows for the particles to pack between cement particles, thus improving void properties of concrete (Mindess, Young, Darwin, 2003). Its high surface area also allows for elimination of segregation and excessive bleeding. Table 2.8 below shows chemical and physical properties of the silica fume used in this investigation.

Table 2. 8: Physical and Chemical Properties of Silica Fume (Batilov, 2016)

Chemical Properties	Testing Results	ASTM C1240 Criteria
Silicon Dioxide	94.72%	85.0% min
Sulfur Trioxide	0.23%	N/A
Chloride	0.11%	N/A
Total Alkali	0.49%	N/A
Moisture Content	0.27%	3.0% max
Loss of Ignition	2.82%	6.0% max
pH	8.47	N/A
Physical Properties		
State of Material	Powder	
Color	Light Grey	
Oversize % Retained on #325 sieve	2.88%	10% max
Density	2.23	N/A
Bulk Density	322.96 kg/m^3	N/A
Specific Surface Area	22.65 m^2/g	15 m^2/g
Average Particle Size	0.1-1 µm	N/A
Accelerated Pozzolanic Activity Index – with Portland cement at 7 days	1330.4%	105 min

2.1.6 Water

If water is potable then it can be used in the mixing process of concrete and does not need to be tested (Mindess, Young, Darwin, 2003). If the water is not potable, then ASTM C94 requires testing of the water. For this study, tap water was used to batch the studied concrete mixtures.

2.2 Mixture Proportioning

In the first phase of the investigation, the selected w/cm were 0.35, 0.4, 0.45, whereas the w/cm were reduced to 0.35 and 0.45 were used for the second phase of the study. The cement content for the first phase were 330 (556), 380 (641), 430 (725), 480 (809), and 530 kg/m^3 (893 lb/yd^3), cement content of 430 kg/m^3 (725 lb/yd^3) and 530 kg/m^3 (893 lb/yd^3) for the second phase. Once the w/cm and cement content were selected, the amount of coarse aggregate, fine aggregate, water were calculated. The amount of coarse aggregate was determined by knowing the bulk volume of the coarse aggregate. The volume of fine aggregate was calculated by deducing total concrete volume from the volumes occupied by, water, coarse aggregate, and entrapped air. Using absolute volume formula, weight of fine aggregated was determined. The water content was calculated by multiplying the w/cm by the cement content. Once the weight of concrete constituents based on one cubic meter (one cubic yard) of concrete was determined, these weights were proportioned for the needed batch volume of the studied concrete mixtures. The required HRWR to maintain the uniform workability was determined through various trials. Table 2.9 documents the mixture proportions of the studied concretes without SCMs that were utilized for the first phase of the study. Table 2.10 presents mixture proportions of the mixtures used for the second phase of the investigation where a portion of Portland cement was replaced with either flag ash, slag, or silica fume.

Table 2. 9: Mixtures Used in the First Phase of Study without SCMs

Cement Content (kg/m^3-w/cm)	Cement Content (lb/yd^3-w/cm)
530-0.35	893-0.35
480-0.35	809-0.35
430-0.35	725-0.35
530-0.40	893-0.40
480-0.40	809-0.40
430-0.40	725-0.40
380-0.40	641-0.40
530-0.45	893-0.45
480-0.45	809-0.45
430-0.45	725-0.45
380-0.45	641-0.45
330-0.45	556-0.45

Table 2. 10: Mixtures Used in the Second Phase of Project with SCMs

Cement Content (kg/m^3-w/cm)	Cement Content (lb/ft^3-w/cm)
FA 15% 430-0.35	FA 15% 725-0.35
FA 30% 430-0.35	FA 30% 725-0.35
FA 45% 430-0.35	FA 45% 725-0.35
FA 15% 430-0.45	FA 15% 725-0.45
FA 30% 430-0.45	FA 30% 725-0.45
FA 45% 430-0.45	FA 45% 725-0.45
FA 15% 530-0.35	FA 15% 893-0.35
FA 30% 530-0.35	FA 30% 893-0.35
FA 45% 530-0.35	FA 45% 893-0.35
FA 15% 530-0.45	FA 15% 893-0.45
FA 30% 530-0.45	FA 30% 893-0.45
FA 45% 530-0.45	FA 45% 893-0.45
S 15% 430-0.35	S 15% 725-0.35
S 30% 430-0.35	S 30% 725-0.35
S 45% 430-0.35	S 45% 725-0.35
S 15% 430-0.45	S 15% 725-0.45
S 30% 430-0.45	S 30% 725-0.45
S 45% 430-0.45	S 45% 725-0.45
S 15% 530-0.35	S 15% 893-0.35
S 30% 530-0.35	S 30% 893-0.35
S 45% 530-0.35	S 45% 893-0.35
S 15% 530-0.45	S 15% 893-0.45
S 30% 530-0.45	S 30% 893-0.45
S 45% 530-0.45	S 45% 893-0.45
SF 7.5% 430-0.35	SF 7.5% 27-0.35
SF 7.5% 430-0.45	SF 7.5% 27-0.45
SF 7.5% 530-0.35	SF 7.5% 33-0.35
SF 7.5% 530-0.45	SF 7.5% 33-0.45

2.3 Mixing Sequence

A counter-current pan mixer as shown in Figure 2.1 was used. A uniform mixing sequence was adopted throughout this study. The steps listed below were followed in the order that are mentioned:

1) All raw materials were accurately weighed.
2) Inside of the pan was moistened with a wet paper towel to prevent any loss of concrete moisture during mixing.
3) Coarse aggregate was first added along with approximately a third portion of the required water and mixed for two minutes.
4) Fine aggregate was then added along with a third portion of the water and mixed for an additional two minutes.
5) Portland cement with or without the supplementary cementitious material (fly, ash, slag, or silica fume) and the remaining water were added and mixed for an additional 2 minutes.
6) Lastly, a pre-measured amount of high-range water reducer admixture was added for an additional 2-3 minutes mixing to allow for fresh concrete to reach the required workability.
7) Concrete was then placed into molds and consolidated using a vibratory table as shown in Figure 2.2

Figure 2. 1: Concrete Pan Mixer

Figure 2. 2: Vibratory Table

2.4 Compression Test

Compression tests was conducted using 102 mm x 202 mm (4 in x 8 in) concrete samples. The compression-loading machine with a loading capacity 2,224 kN (500,000 lb) was utilized for the study. The loading rate of compression-loading machine was kept between 0.21MPa/s (30 psi) and 0.28 MPa/s (40 psi/s). The loading rate was as the specified range to reduce any possible variability that could amongst concrete cylinders. Figure 2.3 shows the compression-loading machine that was used in the study.

Figure 2. 3: Compression Loading Machine

2.5 Chloride Ingress Testing Methods

There are multiple methods that can be used to measure the chloride ingress in concrete. For the purpose of the study, rapid chloride migration test (RMT), rapid chloride penetration test (RCPT), and accelerated corrosion test (ACT) were used. RCPT is currently used by many state DOTs as a mean of quality assurance. RMT and accelerated corrosion are not widely used by DOTs since both tests take a longer time to complete. However, both tests require cheaper testing apparatus to conduct the experiments.

2.5.1 Rapid Chloride Migration Test (RMT)

RMT is a destructive test that measures the amount of chloride migration into a 51 mm x 102 mm (2 in x 4 in) concrete disk. Materials and equipment used for RMT are shown in Table 2.11. Once test samples are taken out of the curing room, they were placed inside a vacuumed desiccation chamber for a period of 24 hours, during which in the first three hours there was no liquid inside it. At the end of the three hour mark, a calcium hydroxide ($Ca(OH)_2$) with distilled water solution was added into the desiccation chamber and the vacuum pump was turned off at the four hour mark. After soaking for 20 hours in a calcium hydroxide solution, the test samples were taken out and placed in a setup as depicted in Figure 2.4.

Table 2. 11: Materials and Equipment Required for RMT

Cathode: Used during the test migration	Desiccator: To prepare samples for test
Anode: Used during the test migration	Sodium Hydroxide Solution: 0.3 N distilled with water
Rubber Sleeve: To hold the samples	Calipers: Measure the amount of chloride penetration
Power supply: To apply the voltage	Thermometer: Measures the temperature of the sodium chloride
Sodium Chloride Solution: 3% by mass	Silver Nitrate Solution: Reactant
Distilled water	Vacuum Pump: To prepare samples for test

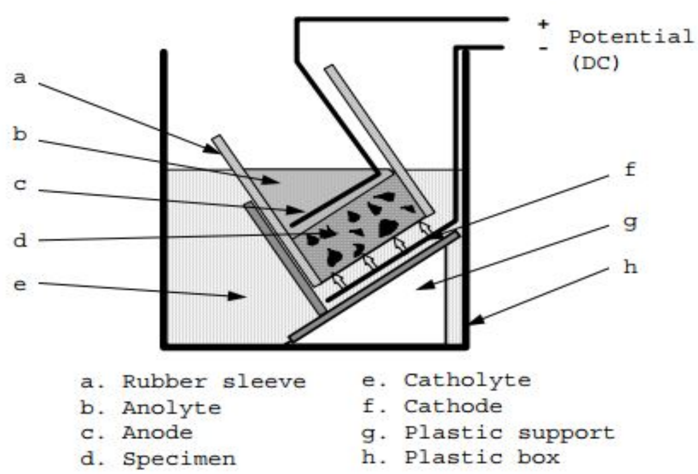

Figure 2. 4: Setup for RMT (NT Build 492)

The inside of the rubber sleeves were filled with a 0.3N sodium hydroxide (NaOH) solution, and inside the plastic tub was filled with sodium chloride (NaCl). A power supply was connected to run at 30V for 24 hours, at the end of the 24 hour the samples were axially split in two equal halves. The exposed insides of the specimens were sprayed with silver nitrate ($AgNO_3$) to show the depth of chloride penetration. Calipers were used to measure the depth of chloride penetration. Figure 2.5 shows the actual setup of the rapid chloride migration test.

Figure 2. 5 RMT Setup (Maler, 2017)

2.5.2 Rapid Chloride Penetration Test (RCPT)

RCPT is another non-destructive test used to measure chloride ion penetration by the amount of charge that passes through a concrete sample in a six-hour test duration. The preparation of the test was similar to the preparation of RMT samples as discussed in the Section 2.5.1. The only difference was that no calcium hydroxide was used during the desiccation of RCPT samples. After the 24-hour desiccation process, the samples were placed in RCPT cells as shown in Figure 2.6.

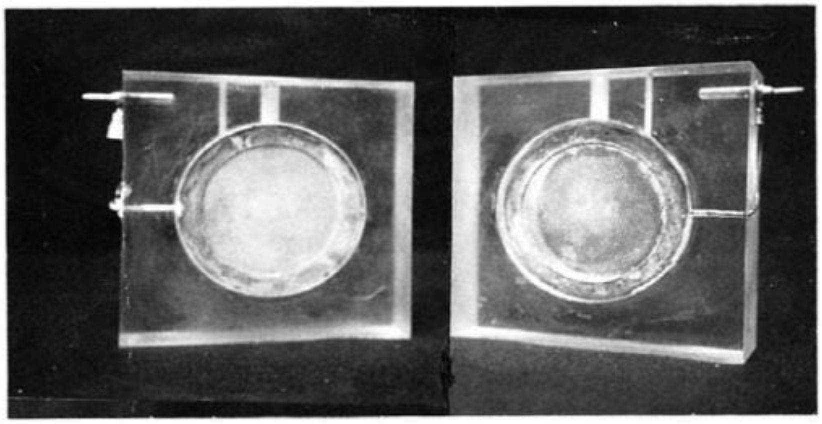

Figure 2. 6: RCPT Cell (ASTM C1202)

One side of the cell was filled with NaOH solution, whereas the other side was filled with a NaCl solution, and the assembled cell was then connected to a machine that measured the number of coulombs pass though the cell in a six-hour period. According to Table 2.12 given by the ASTM C1202, higher RCPT reading relates to higher chloride ion penetrability.

Table 2. 12: RCPT Readings Related to Chloride Ion Penetrability that may be Expected (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

A detailed testing procedure for RCPT is given below.

- The side of the specimens were coated until no more voids were visible.
- Specimens were then placed into a desiccator for a total of 24 hours.
- Vacuum pump was turned on.
- After three hours distilled water was added until the water covered the specimens.
- After four hours the vacuum pump was turn off.
- After 24 hours of being inside the desiccator, the samples were taken out.

- Samples were then placed into the RCPT cells as pictured in Figure 2.7.
- One side of the cell was filled with 3% NaCl, whereas the other side was filled with 0.3N NaOH.
- Wires were then attached to each end of the cells, and a computer software recorded the passing current every 30 minutes.
- The test ran for a total of six hours.

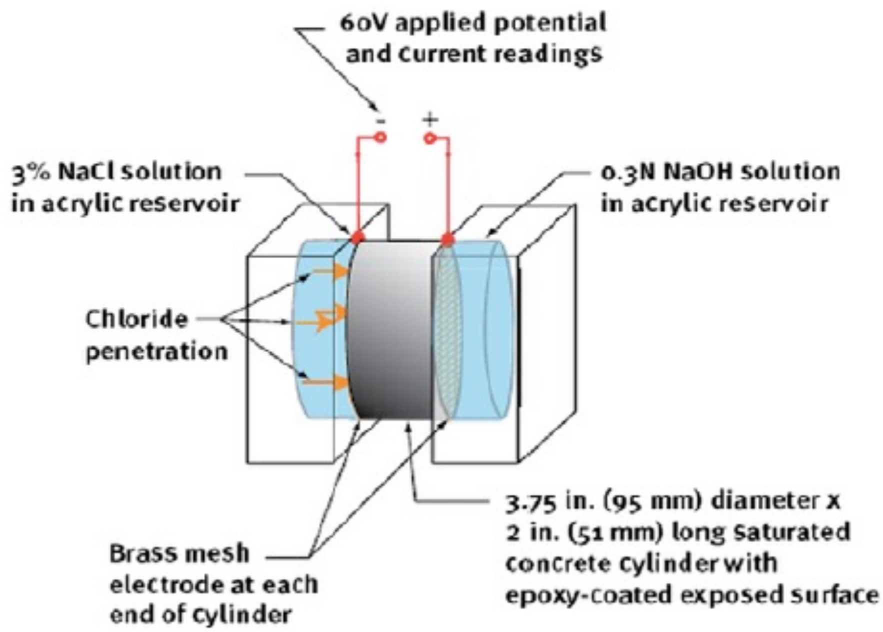

Figure 2. 7: RCPT Schematic (Moradi, 2014)

2.5.3 Accelerated Corrosion Test (ACT)

Accelerated corrosion does not measure the amount of chloride ingress but determines the time it takes for chloride ions to cause specimens to fail via steel corrosion. The test does not have a set amount of time, and it's difficult to predict how long it takes for specimens to fail. Therefore, it's not practical for State DOTs and contractors to use this test for quality assurance. However, the simplicity of the testing is very attractive. The set up for the accelerated corrosion was essentially a battery, a steel bar submerged in 5% NaCl by weight of water solution acting as a cathode, and a concrete specimen with a piece of rebar inserted in the center of the specimen acting as the anode. Both the steel bar and specimens were connected to a power supply, once the power supply was turned on the, Na^+ was attracted to the cathode and the anode attracted to the Cl^-. The current that passed through the samples was also monitored until the samples failed at the formation of first concrete crack. As cracks occurred in the samples, the current readings began to incrementally increase. The test setup is shown in Figure 2.8.

Figure 2. 8: Accelerated Corrosion Setup

2.5.4 Surface Resistivity Test (SRT)

The surface resistivity test is a non-destructive test that utilizes a Wenner four-point array device as shown in Figure 2.9 in schematic form. Figure 2.10 shows the actual device that was used in the study. The two outer pins emit a current differential, which is then measured by the two inner pins. The pins are spring loaded and have water reservoirs that ensure electrical conductivity. In this study, the Wenner probe pins were spaced 38 mm (1.5 in) apart. According to the manufacture's user manual, it's recommended to push the pins in a shallow bucket of water to fill up the reservoirs. The 102 mm x 202 mm (4 in x 8 in) samples were measured at 4 different locations that were spaced 90° from one another. A maker was used to mark the sample to ensure the placement of the device was consistent every time. The measuring time intervals were 0, 10, 20, 30, 40, and 60 minutes.

The step-by-step procedure that was used to conduct SRT is listed below:

- Test samples were taken out of the curing room and dried with paper towels.
- Test samples were then marked with a marker to ensure consistent placement of the pins.
- Test samples were then placed back into curing room for 10 minutes.
- The device was taken out of the box and tested on the provided testing strip to ensure proper functioning.
- Test samples were then taken out of curing room, dried, and measured with the device.
- Finally, test samples were crushed under a compression-loading machine after final surface resistivity measurement was recorded.

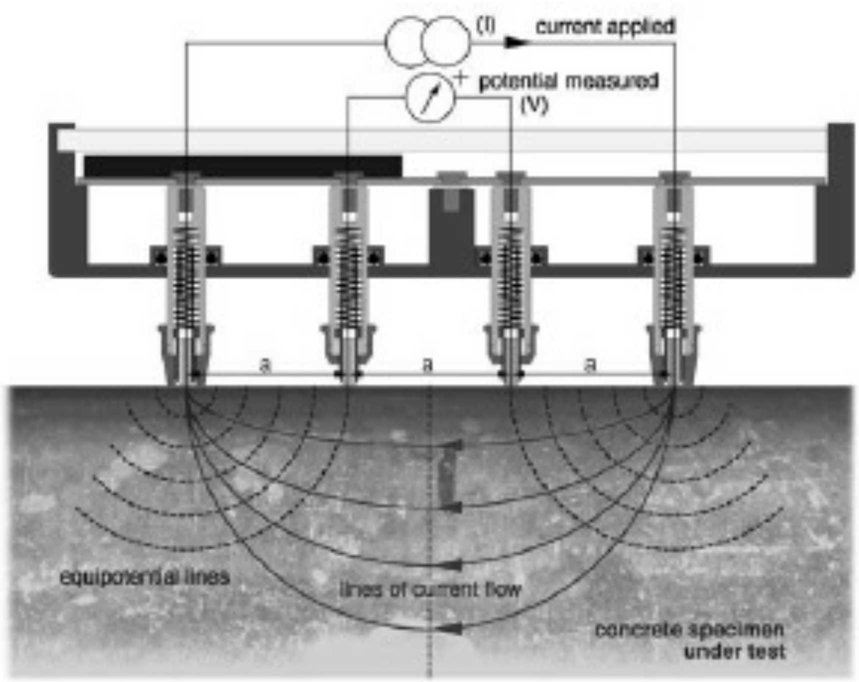

Figure 2. 9: Proceq Wenner Four-Pin Probe Schematic (Proceq Instruction Manual, 2016)

Figure 2. 10: Wenner Probe from the Study

Chapter 3 - Results and Discussion

3.1 Overview

Chapter 3 deals with the presentation and discussion of the results obtained in this study. The results pertaining to the flow and compressive strength of the studied concretes are discussed first, followed by the presentation of the results obtained from RCPT, RMT, SRT, and ACT.

3.2 Slump

The slump test was performed in accordance with the ASTM C143 as a means to determine the uniform consistency of all studied mixtures. It was decided during the planning stages of the study that all studied concretes in the study should have a slump value of 127 mm +/- 25.4 mm (5 in +/- 1 in). When a mixture failed to meet the required flow, it was discarded. The slump values of the studied concretes are presented in Table 3.1 (A and B).

Table 3. 1A: Slump Measurements of the Studied Concretes

Mixtures without SCMs	Slump (in/mm)	Mixtures with Slag	Slump (in/mm)	Mixtures with Fly Ash	Slump (in/mm)	Mixtures with Silica Fume	Slump (in/mm)
530-0.35	5.25/133	S 15% 430-0.35	4.5/114	FA 15% 430-0.35	4.75/121	SF 7.5% 430-0.35	5.5/140
480-0.35	4.5/114	S 30% 430-0.35	5.625/143	FA 30% 430-0.35	5.125/	SF 7.5% 430-0.45	5.25/133
430-0.35	5.5/140	S 45% 430-0.35	6/152	FA 45% 430-0.35	6/152	SF 7.5% 530-0.35	6/152
530-0.40	6/152	S 15% 430-0.45	6/152	FA 15% 430-0.45	5.25/133	SF 7.5% 530-0.45	4.75/121

3.3 Compression Test

The compression test was conducted for the 102 mm x 202 mm (4 in x 8 in) samples after they had gone through the surface resistivity test. This allowed for the efficient utilization of concrete samples produced. A compression-loading machine with a capacity of 2,224 kN (500,000 lb) was used to conduct the compression tests. A minimum of three samples were used to obtain the average compressive strength. The loading rate during the compression test was consistently kept between 0.21MPa/s (30 psi) and 0.28 MPa/s (40 psi/s).

Table 3. 1B: Slump Measurements of the Studied Concretes

Mixtures without SCMs	Slump (in/mm)	Mixtures with Slag	Slump (in/mm)	Mixtures with Fly Ash	Slump (in/mm)
480-0.40	4.875/124	S 30% 430-0.45	4/102	FA 30% 430-0.45	5.5/140
430-0.40	5.625/143	S 45% 430-0.45	5.5/140	FA 45% 430-0.45	6/152
380-0.40	6/152	S 15% 530-0.35	5.875/149	FA 15% 530-0.35	5/127
530-0.45	4.375/111	S 30% 530-0.35	4.5/114	FA 30% 530-0.35	5.375
480-0.45	4.25/108	S 45% 530-0.35	5.75/146	FA 45% 530-0.35	6/152
430-0.45	4.75/121	S 15% 530-0.45	4.875/124	FA 15% 530-0.45	6/152
380-0.45	5.5/140	S 30% 530-0.45	5/127	FA 30% 530-0.45	4.25/108
330-0.45	5.25/133	S 45% 530-0.45	4.75/121	FA 45% 530-0.45	6/152

3.3.1 Impact of Binder Content on Compressive Strength

It was observed during the study that binder content does have an impact on the compressive strength of the studied concrete samples. In general, the higher amount of binder content tended to increase the compressive strength. The impact of binder was evident in the phase two of the study due to increases in SCMs content. In the phase one of the study, the impact of cement on compressive strength was not as pronounced since the compressive strength results were all nearly similar.

3.3.1.1 Impact of Cement Content on Compressive Strength

The increase in cement content did improve the averaged compressive strength and the results are shown in Table 3.2 and Figure 3.1. As can be seen, the increase in the compressive strength plateaued at the level of 430 kg/m^3 of cement factor, after which it remained fairly uniform with additional increases in cement content. The same pattern emerged with an increase in concrete age.

The increase in cement content from 330 kg/m^3 (556 lb/yd^3) to 380 kg/m^3 (641 lb/yd^3) resulted in an increase in compressive strength of 26%, whereas the compressive strength improved by nearly 5.7% once cement content increased from 380 (641 lb/yd^3) to 430 kg/m^3 (725 lb/yd^3) in the 28-day results. Additional increases in cement content resulted in minimal changes in the compressive strength of the studied cement concretes.

Table 3. 2: Average Compressive Strength of Samples from Phase 1 (No Cement Replacement)

Cement Content (kg/m^3)	28 Days (psi)	28 Days (MPa)	90 Days (psi)	90 Days (MPa)	Percent Difference Between 28- and 90-day Measurements (%)
530	8439	58	10186	70	19
480	8334	57	10294	71	22
430	8558	59	10312	71	18
380	8096	56	9689	67	18
330	6791	47	8325	57	19

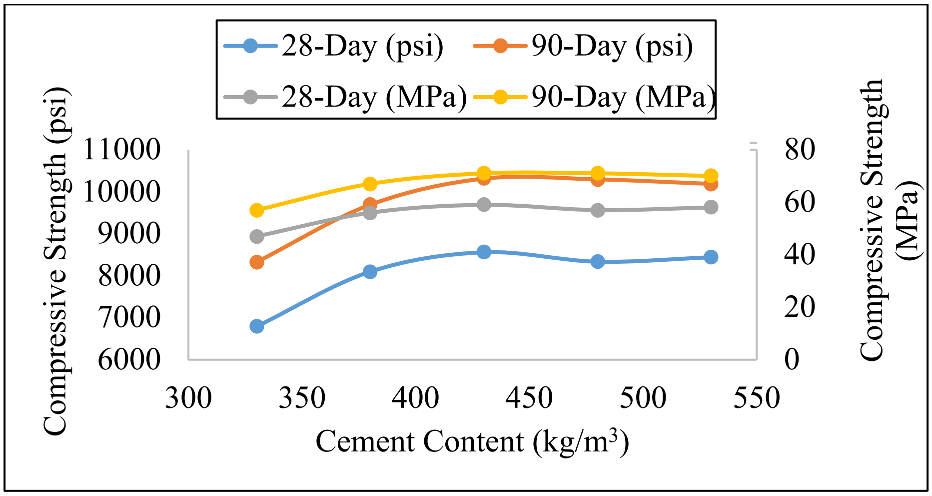

Figure 3. 1: Impact of Cement Content on Compressive Strength without SCMs

3.3.1.2 Impact of Fly Ash on Compressive Strength

The higher percentage of fly ash replacing Portland cement resulted in a greater reduction in the compressive strength of the studied concretes. Table 3.3 (A and B) shows the averaged compressive strengths from all mixtures containing fly ash. The lowest recorded compressive strength in the study was the mixture with the highest amount of fly ash, cement, and w/cm. With the addition of fly ash, the average increase in 28- to 90-day compressive strength was about 32%. In comparison, the average increase in the 28- to 90-day compressive strengths of the concrete without fly ash was approximately 20%. The water-to-cementitious materials ratio adversely affected the compression test results. Average reductions of 10 and 3% in the 28- and 90-day compressive strengths were noticed when fly ash content replaced 15% by weight of Portland cement, respectively. Once fly ash replaced 30% by weight of cement, these reductions increased to 21% and 10%, respectively. A replacement of 45% resulted in more averagely reductions of 36% and 29% for the 28- and 90-day compressive strengths, respectively.

Table 3. 3A: Average Compressive Strength Results of Fly Ash Concretes

Cement Content with Replacement (kg/m^3-w/cm)	28 Days (psi)	28 Days (MPa)	Percent Decrease between Mixtures with and without Fly Ash (28-Day)	90 Days (psi)	90 Days (MPa)	Percent Decrease between Mixtures with and without Fly Ash (90-Day)	Percent Increase Between 28- and 90-day Results (%)
430-0.35	9472	65		11544	80		
FA 15% 430-0.35	9387	65	1	11961	82	-4	27
FA 30% 430-0.35	8069	56	15	11203	77	3	39
FA 45% 430-0.35	6785	47	28	8752	60	24	29
430-0.45	7854	54		9275	64		
FA 15% 430-0.45	6796	47	13	8914	61	4	31
FA 30% 430-0.45	6054	42	23	7991	55	14	32
FA 45% 430-0.45	4014	28	49	6163	42	34	54

Table 3. 3B: Average Compressive Strength Results of Fly Ash Concretes

Cement Content with Replacement (kg/m^3-w/cm)	28 Days (psi)	28 Days (MPa)	Percent Decrease between Mixtures with and without Fly Ash (28-Day)	90 Days (psi)	90 Days (MPa)	Percent Decrease between Mixtures with and without Fly Ash (90-Day)	Percent Increase Between 28- and 90-day Results (%)
530-0.35	9820	68		11498	79		
FA 15% 530-0.35	8667	60	12	11035	76	4	27
FA 30% 530-0.35	7782	54	21	10132	70	12	30
FA 45% 530-0.35	6968	48	29	8766	60	24	26
530-0.45	7616	53		9329	64		
FA 15% 530-0.45	6402	44	16	8283	57	11	29
FA 30% 530-0.45	5683	39	25	7971	55	35	40
FA 45% 530-0.45	4445	31	42	6069	42	38	37

3.3.1.3 Impact of Slag on Compressive Strength

The results of the compression tests for the studied concretes containing slag are shown in Table 3.4. The optimum amount of slag for a concrete mixture is approximately 40% of binder content, after which the ultimate strength ratio will begin to decrease (Lee et. al, 2015). The compressive strength of mixtures with slag were slightly lower or nearly the same as the companion mixtures with no Portland cement substitution. Compressive strength of the mixtures with slag were considerably higher than that of the fly ash concretes. The impact of w/cm and slag addition on compressive strength was significantly below that experienced with fly ash addition. The 28-day compressive strength of concrete reduced averagely by 3% for every 15% substitution by weight of Portland cement with slag. Once curing time was extended to 90 days, the reduction in the compressive strength of the slag concretes stood at 10%.

Table 3. 4: Average Compressive Strength Results of Slag Concretes

Cement Content with Replacement (kg/m^3-w/cm)	28 Days (psi)	28 Days (MPa)	Percent Decrease between Mixtures with and without Slag (28-Day)	90 Days (psi)	90 Days (MPa)	Percent Decrease between Mixtures with and without Slag (90-Day)	Percent Increase (%)
430-0.35	9472	65		11544	80		80
S 15% 430-0.35	9505	66	0	10771	74	7	13
S 30% 430-0.35	9658	67	2	10459	72	9	8
S 45% 430-0.35	10299	71	9	11471	79	1	11
430-0.45	7854	54		9275	64		64
S 15% 430-0.45	7288	50	7	8365	58	10	15
S 30% 430-0.45	7829	54	7	8621	59	7	10
S 45% 430-0.45	7542	52	4	8726	60	6	16
530-0.35	9820	68		11498	79		79
S 15% 530-0.35	9037	62	8	10456	72	9	16
S 30% 530-0.35	9395	65	4	10728	74	7	14
S 45% 530-0.35	9423	65	4	10040	69	13	7
530-0.45	7616	53		9329	64		64
S 15% 530-0.45	7122	49	6	8169	56	12	15
S 30% 530-0.45	7212	50	5	7807	54	16	8
S 45% 530-0.45	7285	50	4	8066	56	14	11

3.3.1.4 Impact of Silica Fume on Compressive Strength

Silica fume only impacted the compressive strength of concrete slightly. Table 3.5 presents the averaged compressive strength results of the studied concrete containing silica fume. The change of compressive strength between the 28- and 90-day silica fume samples were not that substantial. A uniform replacement of 7.5%, for the two different content factors, did not have any impact on the compressive strength of the studied silica fume concretes. Table 3.5 also shows that the compressive strengths of the mixtures containing silica fume were marginally different from that of the concretes with zero percentage of cement replacement. An increase in the water-to-cementitious materials ratio had an adverse effect on the compressive strength of silica fume concretes. However, these reductions were moderately lower than that of the fly ash and slag concretes. An increase of w/cm from 0.35 to 0.45 resulted in the averagely reductions of the 18% and 22% for the 28- and 90-day concrete compressive strength, respectively.

Table 3. 5: Average Compressive Strength Results of Silica Fume Concretes

Cement Content with Replacement (kg/m^3-w/cm)	28 Days (psi)	28 Days (MPa)	90 Days (psi)	90 Days (MPa)	Percent Difference Between 28- and 90-day Results with and without Silica Fume (%)
430-0.35	9472	65	11544	80	
SF 7.5% 430-0.35	9658	67	10971	76	14
430-0.45	7854	54	9275	64	
SF 7.5% 430-0.45	7831	54	9059	62	16
530-0.35	9820	68	11498	79	
SF 7.5% 530-0.35	9646	67	11040	76	14
530-0.45	7616	53	9329	64	
SF 7.5% 530-0.45	8068	56	8178	56	1

3.3.2 Influence of Age on Compressive Strength

The impacts of curing age on compressive strength was also examined. As it can be seen from Tables 3.2 through 3.5 that an extension of curing age resulted in the increase of the compressive strength of the studied concretes. The averaged percentage of improvement in the compressive strength with the increase in concrete age from 28 to 90 days were 25, 12, 11% for the mixtures incorporating fly ash, slag, and silica fume, respectively.

3.3.3 Influence of Water-To-Cementitious Materials Ratio on Compressive Strength

The w/cm had the opposite effect on the compressive strength of the studied concretes. In all cases, the compression strength results were lower when w/cm increased. It's was expected prior to the study that the higher w/cm would lower the strength of the concrete. The impact of w/cm on compressive strength can be observed in Tables 3.3 through 3.5. An increase in w/cm for 0.35 to 0.45 resulted in the averagely decreases in the compressive strength of 28, 22, and 20%, respectively, for the concretes containing fly ash, slag, and silica fume.

3.4 Rapid Chloride Penetrability Test (RCPT) Results

The Rapid Chloride Penetration Test is currently utilized by a number of State DOTs as a mean for quality assurance of concrete mixtures. If the RCPT reading (charged pass) is high, it means concrete has a lower resistance to the penetration of chloride ions. The results of the test are impacted by the chemistry of the pore solution and by the pore structure of the concrete (Moradi, 2014). Other factors impacting RCPT results are aggregate type and content, cement composition and factor, aggregate fine to coarse ration, and supplementary cementitious materials. The range of charge passed can vary from less than 100 coulombs to over 4000 coulombs (ASTM, 2017). A drawback of the RCPT test is that it measures the movement of all ions into the concrete and not just the chloride ions (Hooton et al., 1997). Appendix A will contain the non-averaged RCPT results for all concretes.

3.4.1 Impact of Binder Content on RCPT Results

The following sections are in regard to the various binder contents and materials that were used in the study. In the phase two of the study; fly ash, slag, and silica fume were used to replace a portion of Portland cement. Fly ash and slag replaced 15, 30, and 45% by weight of Portland cement, whereas silica fume substituted 7.5% of Portland cement. The results of the experimental study pertaining to the phases one and two are presented in the forthcoming sections.

3.4.1.1 Impact of Cement Content on RCPT Results

The impact of the cement content on RCPT results are discussed in the section. In the first phase of the study, five different cement contents were used, while the second phase of the study utilized two cement factors containing cementitious materials.

As shown in Table 3.6, the increased cement content also increased the RCPT results. Figure 3.6 shows the increase in coulombs as functions of cement content. An increase of 50 kg/m^3 (84 lb/yd^3) in cement factor resulted in an averagely increase of 376 coulombs, whereas an increase of curing age from 28 to 90 day caused an averagely reduction in coulomb by nearly 50% in the concrete samples without SCMs.

Table 3.7 documents the results of the second phase of the study in which a portion of Portland cement was replaced by supplementary cementitious materials. Similar to the results presented in Table 3.6, the higher cement contents resulted in higher coulombs, and the 90-day results were all lower than the 28-day results. The percentage of decrease in the phase two of the study between the 28- and 90-day results were not as large as shown in Table 3.6. Addition of the silica fume resulted in lowest RCPT result, followed by the slag and fly ash respectively. The percentage of decrease of the RCPT results, as shown in Table 3.7, ranged from as low as 31% to as high as 67%.

Table 3. 6: Average Charge Passed (Coulombs) of 28- and 90-Day Samples without SCMs

Cement Content (kg/m^3)	28 Days (Coulombs)	90 Days (Coulombs)	Percent Decrease (%)
530	5377	2789	93
480	4676	2294	104
430	3735	1792	108
380	3619	1801	101
330	3562	1596	123

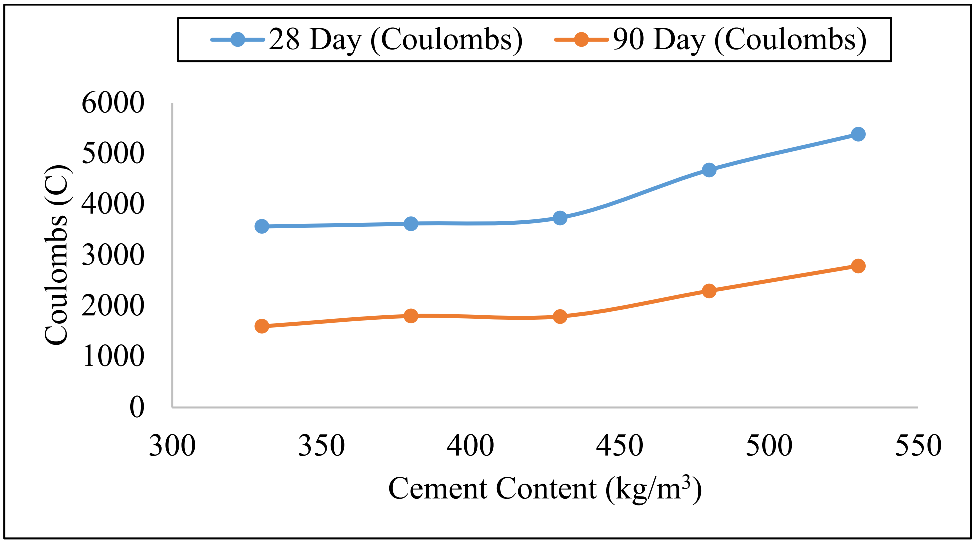

Figure 3. 2: RCPT Results from First Phase of Study with No Cement Replacement

Table 3. 7: Average Charge Passed (Coulombs) of 28- and 90-Day Samples with SCMs

Cement Content with Replacement (kg/m^3-w/cm)	28 Days (Coulombs)	90 Days (Coulombs)	Percent Decrease (%)
Slag 430-0.35	973	671	31
Slag 430-0.45	1535	1019	34
Slag 530-0.35	1297	788	39
Slag 530-0.45	2284	1388	39
Fly Ash 430-0.35	1489	484	67
Fly Ash 430-0.45	2089	715	66
Fly Ash 530-0.35	1150	572	50
Fly Ash 530-0.45	2515	925	63
Silica Fume	550	343	38

3.4.1.2 Influence of Fly Ash on RCPT Results

Table 3.8 shows the results of concrete samples in phase two of the study in which fly ash replaced a portion of Portland cement. The percentages of Portland cement replacement were 15%, 30%, and 45%. While the initial cement content and w/cm stayed constant, the replacement percentage were increased to examine the impact the fly ash will have on RCPT results. The trend for all studied fly ash concretes was very consistent; the higher the percentage of cement replacement at the uniform cement factor and w/cm, the lower RCPT results. The percentage of decrease in coulombs from 28- to 90-day fly ash concretes ranged from 53% to 72%.

Once 15% by weight of the Portland cement was replaced with fly ash, the 28-day and 90-day RCPT results reduced averagely by 35% and 50%, respectively. The 30% by weight substitutions of Portland cement generated an approximately 56% and 72% for the two curing ages. Additional replacement to 45% by weight of Portland cement further reduced the results by 77% and 84%, respectively, when compared to those produced by concretes containing no fly ash.

The age did not have as much of an impact when compared to the results in Table 3.6. The decrease of percentage with the use of fly ash was an average of 65%. Overall, the fly ash did aid in the prevention of chloride ions from penetrating into the concrete. The fineness of the fly ash, which causes a denser microstructure, allows for concrete to better resist chloride ingress (Dhir and Jones, 1999).

Table 3. 8: Average Charge Passed (Coulombs) of 28- and 90-Day Fly Ash Concretes

Cement Content with Replacement (kg/m^3-w/cm)	28 Days (Coulombs)	Percent Decrease between Mixtures with and without Fly Ash (28-Day)	90 Days (Coulombs)	Percent Decrease between Mixtures with and without Fly Ash (28-Day)	Percent Decrease Between 28- and 90-Day Results (%)
430-0.35	2658		1135		
FA 15% 430-0.35	2446	8	755	33	69
FA 30% 430-0.35	1347	49	437	61	68
FA 45% 430-0.35	675	75	261	77	61
430-0.45	4887		2557		
FA 15% 430-0.45	3047	38	1081	58	65
FA 30% 430-0.45	2025	59	693	73	66
FA 45% 430-0.45	1196	76	370	86	69
530-0.35	3758		1834		
FA 15% 530-0.35	2001	47	936	49	53
FA 30% 530-0.35	1678	55	506	72	70
FA 45% 530-0.35	943	75	274	85	71
530-0.45	3758		1834		
FA 15% 530-0.45	3557	46	1599	60	55
FA 30% 530-0.45	2740	59	762	81	72
FA 45% 530-0.45	1249	81	413	90	67

3.4.1.3 Impact of Slag on RCPT Results

The RCPT results pertaining to incorporation of slag as a partial substitution for Portland cement are shown in Table 3.9 (A and B). In general, slag had a positive effect on the RCPT results and its influence increased with an increase in slag content. An increase in concrete age produced a better chloride ion resistance, whereas an increase in w/cm did the contrary. For each 15% increase in cement replacement, the studied 28- and 90-day slag concretes reduced the measured coulombs by averages of 66% and 60%, respectively. The results were lower than those of the fly ash concretes shown in Table 3.8. A study conducted by the NJDOT also showed that the mixtures with slag had the lower readings when compared to that of fly ash concretes (Nassif, Rabie, Na, Salvador, 2015).

Once concrete age was extended from 28 to 90 days, the RCPT results of slag concretes reduced by an averagely of 36 parentage. The increase of w/cm from 0.35 to 0.45 increased coulombs by an approximately 35% and 37% for the 28- and 90-day slag concretes.

Table 3. 9A: Average Charge Passed (Coulombs) of 28- and 90-Day Slag Concretes

Cement Content with Replacement (kg/m^3-w/cm)	28-Day (Coulombs)	Percent Decrease between Mixtures with and without Slag (28-Day)	90-Day (Coulombs)	Percent Decrease between Mixtures with and without Slag (90-Day)	Percent Decrease Between 28- and 90-Day Results (%)
430-0.35	2658		1135		
S 15% 430-0.35	1358	49	864	24	36
S 30% 430-0.35	973	124	704	38	28
S 45% 430-0.35	588	213	445	61	24
430-0.45	4887		2557		
S 15% 430-0.45	2188	55	1429	44	35
S 30% 430-0.45	1479	70	1014	60	31
S 45% 430-0.45	937	81	614	76	34

Table 3. 9B: Average Charge Passed (Coulombs) of 28- and 90-Day Slag Concretes

Cement Content with Replacement (kg/m^3-w/cm)	28-Day (Coulombs)	Percent Decrease between Mixtures with and without Slag (28-Day)	90-Day (Coulombs)	Percent Decrease between Mixtures with and without Slag (90-Day)	Percent Decrease Between 28- and 90-Day Results (%)
530-0.35	3758		1834		
S 15% 530-0.35	1878	50	1055	42	44
S 30% 530-0.35	1198	68	820	55	32
S 45% 530-0.35	815	78	488	73	40
530-0.45	6648		3962		
S 15% 530-0.45	3484	48	1997	50	43
S 30% 530-0.45	2024	70	1479	63	27
S 45% 530-0.45	1345	80	687	83	49

Table 3. 10: Average Charge Passed (Coulombs) of 28- and 90-Day Silica Fume Concretes

Cement Content (kg/m^3)	28 Days (Coulombs)	90 Days (Coulombs)	Percent Decrease Between Silica Fume Mixture and Without Mixture 28-Day (%)	Percent Decrease Between Silica Fume Mixture and Without Mixture 90-Day (%)
430-0.35	2658	1135		
SF 7.5% 430-0.35	347	212	87	81
430-0.45	4887	2557		
SF 7.5% 430-0.45	682	400	86	84
530-0.35	3758	1834		
SF 7.5% 530-0.35	374	285	90	90
530-0.45	6648	3962		
SF 7.5% 530-0.45	796	475	88	88

3.4.2 Influence of Age on RCPT Results

Irrespective of the type and content of the SCMs, concrete age had a positive impact on impeding the movement of chloride ions into concrete. Tables 3.6 through 3.10 shows that the coulombs in the 90-day samples were all lower than the 28-day counterparts. Table 3.11

demonstrates average decreases in columns once curing age was extended from 28 to 90 days.

3.4.3 Influence of Water-To-Cementitious Material Ratio on RCPT Results

The influence of w/cm on all studied concretes was also consistent as documented in Tables 3.6 through 3.10. Table 3.11 and Figure 3.3 shows average increases in charged passed for the studied concretes without SCMs with increase in w/cm.

Table 3. 11: Average Charge passed for 28- and 90-Day Concretes without SCMs Based on w/cm

w/cm	28 Days (Coulombs)	90 Days (Coulombs)	Percent Increase (%)
0.35	3139	1271	147
0.4	4204	1875	124
0.45	5112	2659	92

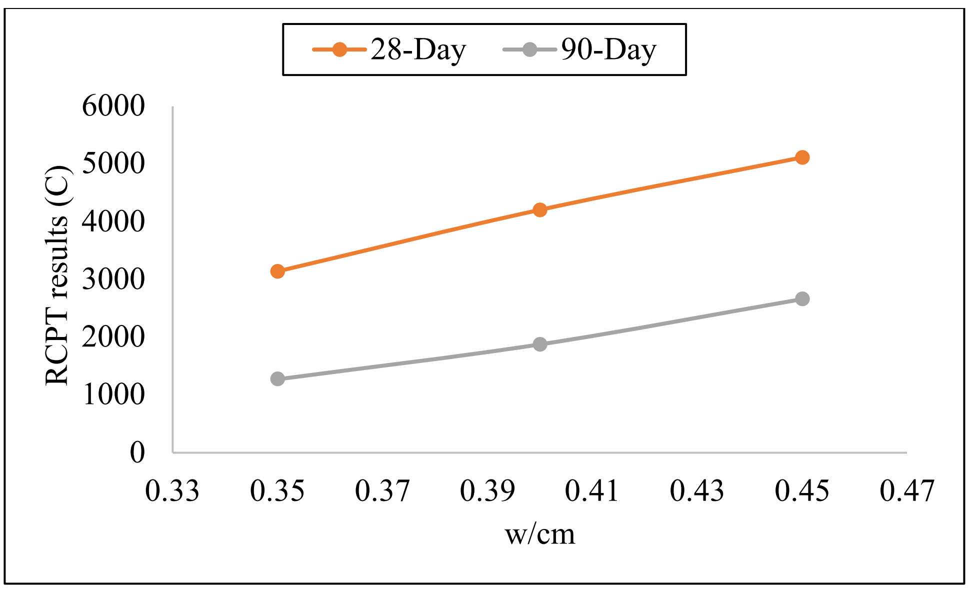

Figure 3. 3: Impact of w/cm on RCPT Results for concretes with no SCMs

3.5 Rapid Chloride Migration Test (RMT) Results

As discussed in Chapter 2, RMT is a destructive test that that measures the depth of chloride migration via physically breaking concrete samples in half axially. Once concrete samples were halved, a silver nitrate solution was sprayed onto the halved samples, and a caliper was used to measure the amount of coloration as a depth of chloride ion migration into concrete samples. In general, the results of the study showed that the increase in replacement percentage and concrete age decreased the amount of chloride ion migration. Comparatively, a larger water-to-cementitious materials ratio content increased the amount of ion migration into the studied concretes. An increased amount of cement, or an increase in the amount of cement replaced with SCMs, caused the depth of migration to decrease as well. Mixtures that had silica fume decreased the amount of chloride ion migration more than concretes with slag and fly ash. The following sections discusses the RMT results pertaining to the impact of binder content, age, and w/cm. Appendix B will contain the measured depths of chloride penetration for concretes from both phases of the study.

3.5.1. Impact of Binder Content on RMT Results

In general, the higher amount of binder content resulted in a decrease of chloride ion migration. The increases in supplementary cementitious materials and Portland cement improved the ability of the concrete samples to resist the migration of ions. Out of the three supplementary cementitious materials utilized in the study, silica fume decreased the amount of chloride ions migration the most. For the 90-day silica fume concrete samples, the amount of migration became miniscule.

3.5.1.1 Impact of Cement Content on RMT Results

Table 3.12 shows the impact of cement content on the averaged depth of chloride ion migration. Figure 3.4 displays the trend in the depth of chloride ions migration as functions of cement content.

It can be seen that the cement content decreased the depth of migrated chloride ions. However, these averaged decreases were not as significant with variation in cement contents. The decrease of ion migration, due to the increased cement content, was similar to a study conducted by Maler in 2017. The percentage of change between 28- and 90-day samples was fairly uniform at about 30% percent.

Table 3.13 shows the impact of cement content when SCMs were used at different water-to-cementitious materials ratios. It was observed that the trend of a decrease in depth of ion migration due to the increase of w/cm remained unchanged even with the presence of supplementary cementitious materials. While the w/cm was kept constant and as the cement content increased, the depth of chloride ion migration did not change dramatically. The most drastic change of migration can be observed in the mixtures in which the cement content was kept constant, but the w/cm was changed. There was an approximate 4 mm (0.16 in) to 6 mm (0.24 in) of increase in the RMT results when the w/cm was increased from 0.35 to 0.45.

Table 3. 12: Depth of Chloride Ion Migration Based on Cement Content in Phase 1

Cement Content (kg/m^3)	28 Days (in)	28 Days (mm)	90 Days (in)	90 Days (mm)	Percent Difference (%)_
530	1.11	28.19	0.61	15.58	80.98
480	1.01	25.65	0.58	14.82	73.14
430	1.15	29.13	0.60	15.16	92.18
380	1.26	31.88	0.66	16.76	90.15
330	1.58	40.13	0.76	19.30	107.89

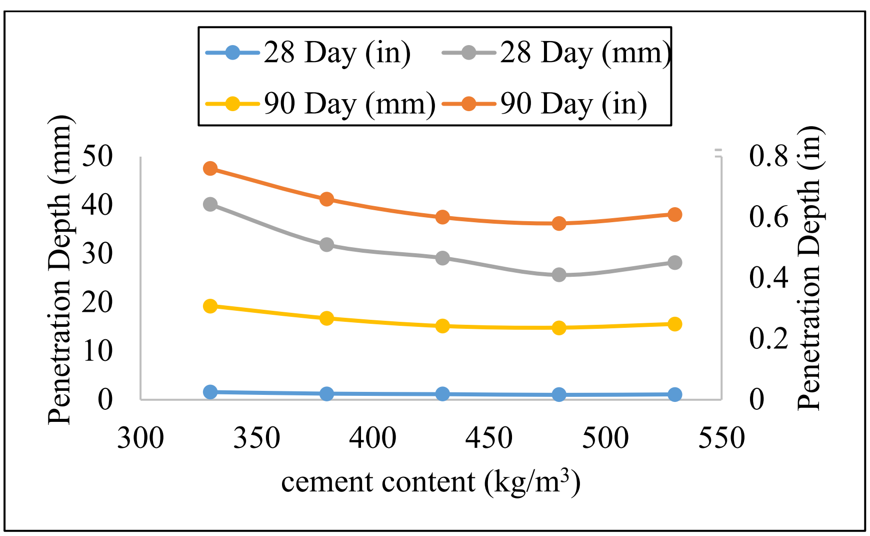

Figure 3. 4: Depth of Penetration of Specimens due to Cement Content without SCMs

Table 3. 13: Average Depth of Chloride Ion Migration of 28- and 90-Day SCMs Contained Concretes

Cement Content with Replacement (kg/m^3-w/cm)	28-Day (in)	28-Day (mm)	90-Day (in)	90-Day (mm)	Percent Difference Between 28- and 90-Day Results (%)
Slag 430-0.35	0.40	10.24	0.28	7.20	29.75
Slag 430-0.45	0.53	13.55	0.36	9.14	32.50
Slag 530-0.35	0.41	10.41	0.29	7.37	29.27
Slag 530-0.45	0.57	14.48	0.40	10.08	30.41
Fly Ash 430-0.35	0.71	18.03	0.23	5.93	67.14
Fly Ash 430-0.45	0.88	22.27	0.30	7.70	65.40
Fly Ash 530-0.35	0.63	16.09	0.24	6.10	52.63
Fly Ash 530-0.45	0.89	22.52	0.33	8.30	63.16
Silica Fume	0.24	6.10	0.14	3.56	41.67

3.5.1.2 Impact of Fly Ash on RMT Results

Table 3.14 shows the depth of ion penetration of twelve mixtures containing fly ash, with varying amounts of cement factor and w/cm. Similarly to the increase of cement content, the usage of fly ash also decreased the depth of chloride ion migration. When the cement content and w/cm was kept constant, and as the percentage of replacement was increased, the depth of ion migration decreased. When fly ash replaced 15% of Portland cement by weight, the RMT results reduced averagely by nearly 48 and 50% for the 28- and 90-day concretes, respectively. An increase of fly ash addition to 30% reduced to depth of ion migration by an average of 28 and 50%, respectively, for the two curing ages. Once fly ash replaced 45% by weight of Portland cement, the decreases in the RMT results were at the level of 50 and 71% for 28- and 90-day concretes. On the average, an increase in the concrete age reduced the depth of chloride ion migration by approximately 68%. An increase of water-to-cementitious materials ratio from 0.35 to 0.45 increased RMT results by nearly 64 and 70% for the 28- and 90-day samples. Fly ash, due to its fine size particles, was able to fill the space between the calcium silicate hydrate (CSH) gels, blocking the capillary pores, thus not allowing chloride ion migration into the concrete (Liu et al, 2014).

Table 3. 14: Average Depth of Chloride Ion Migration of 28- and 90-Day Fly Ash Concretes

Cement Content with Replacement (kg/m^3-w/cm)	28 Days (in)	28 Days (mm)	Percent Decrease Between Fly Ash Mixture and Without Mixture 28-Day (%)	90 Days (in)	90 Days (mm)	Percent Decrease Between Fly Ash Mixture and Without Mixture 90-Day (%)	Percent Difference (%)
430-0.35	0.98	24.89		0.45	11.43		
FA 15% 430-0.35	0.94	23.88	4	0.33	8.38	27	65
FA 30% 430-0.35	0.67	17.02	32	0.25	6.35	44	63
FA 45% 430-0.35	0.52	13.21	47	0.12	3.05	73	77
430-0.45	1.29	32.77		0.74	18.80		
FA 15% 430-0.45	1.1	27.94	15	0.04	1.02	95	96
FA 30% 430-0.45	0.98	24.89	24	0.3	7.62	59.	69
FA 45% 430-0.45	0.55	13.97	57	0.21	5.33	72	62
530-0.35	0.95	24.13		0.48	12.19		49
FA 15% 530-0.35	0.71	18.03	25	0.3	7.62	38	58
FA 30% 530-0.35	0.67	17.02	29	0.29	7.37	40	57
FA 45% 530-0.35	0.52	13.21	45	0.13	3.30	73	75
530-0.45	1.23	31.24		0.72	18.29		
FA 15% 530-0.45	1.17	29.72	5	0.44	11.18	39	62
FA 30% 530-0.45	0.88	22.35	28	0.31	7.87	57	65
FA 45% 530-0.45	0.61	15.49	50	0.23	5.84	68	6

3.5.1.3 Impact of Slag on RMT Results

A total of twelve concretes containing slag at various substitutions for Portland cement were produced. The slag concretes had the same proportions of cement content, w/cm, and cement replacement percentages as the fly ash concretes. Table 3.15 summarizes the averaged RMT results of the studied slag concretes. Overall, a replacement of 15, 30, and 45% by weight of Portland cement, reduced the depth of migration of ions into 28-day slag concretes by average of 43, 56, and 71%, respectively. The 90-day slag concretes having the same percentages of cement replacement produced averagely decreases in time RMT results of 23%, 46%, and 64%, respectively.

An increase in curing age from 28 to 90 days decreased the depth of ion migration by nearly 27, 33, and 33% when slag substituted 15, 30, and 45% by weight or Portland cement. The increase in water-to-cementitious materials ration from 0.35 to 0.45 resulted in increases of 34 and 31% in the depth of migrated chloride ions for the 28-day and 90-day slag concretes.

Table 3. 15: Average Depth of Chloride Ion Migration of 28- and 90-Day Slag Concretes

Cement Content with Replacement (kg/m^3-w/cm)	28 Days (in)	28 Days (mm)	Percent Decrease Between with and without slag 28-Day (%)	90 Days (in)	90 Days (mm)	Percent Decrease Between with and without slag 90-Day (%)	Percent Difference Between 28-and-90 Day Results (%)
430-0.35	0.98			0.45			
S 15% 430-0.35	0.57	14.48	41.84	0.37	9.40	17.78	35
S 30% 430-0.35	0.38	9.65	61.22	0.28	7.11	37.78	26
S 45% 430-0.35	0.26	6.60	73.47	0.2	5.08	55.56	2
430-0.45	1.29			0.74			
S 15% 430-0.45	0.72	18.29	44.19	0.51	12.95	31.08	29
S 30% 430-0.45	0.54	13.72	58.14	0.34	8.64	54.05	37
S 45% 430-0.45	0.34	8.64	73.64	0.23	5.84	68.92	32
530-0.35	0.95			0.48			
S 15% 530-0.35	0.5	12.70	47.37	0.38	9.65	60.00	24
S 30% 530-0.35	0.44	11.18	53.68	0.29	7.37	69.47	34
S 45% 530-0.35	0.29	7.37	69.47	0.2	5.08	78.95	31
530-0.45	1.23			0.72			
S 15% 530-0.45	0.74	18.80	39.84	0.58	14.73	52.85	22
S 30% 530-0.45	0.59	14.99	52.03	0.39	9.91	68.29	34
S 45% 530-0.45	0.38	9.65	69.11	0.22	5.59	82.11	42

When the RMT results of the slag concretes are compared to the results of the equivalent fly ash mixtures, it can be seen that that slag was more effective at preventing the migration of chloride ions.

3.5.1.4 Impact of Silica Fume on RMT Results

As shown in Table 3.16, silica fume concretes decreased the depth of chloride ion migration even when a small amount of silica fume replaced a portion of Portland cement (7.5%

by weight). The increase of concrete age reduced the depth of migrated chloride ions by nearly 42%. When w/cm increased from 0.35 to 0.45, the RMT results averagely increased by approximately 71%. The percent decrease in the RMT results between the mixtures with and without silica fume was approximately 82%. For the 90-day results, there seems to be a diminishing return in the amount of cement since there was not a major of difference between the silica fume samples that have the same w/cm. There was only 0.76 mm (0.03 in) difference between the 0.35 w/cm silica fume concretes and 1.02 mm (0.04 in) of difference between the 0.45 w/cm mixtures containing silica fume. The above-mentioned results indicate that silica fume concrete can greatly improve the ability of concrete to resist chloride ion migration, thus significantly decreasing the likelihood of corrosion of rebar and enhancing the longevity of concrete.

Table 3. 16: Average Depth of Chloride Ion Migration of 28- and 90-Day Silica Fume Concretes

Cement Content with Replacement (kg/m^3-w/cm)	28 Days (in)	28 Days (mm)	Percent Decrease Between With and Without SF 28-Day (%)	90 Days (in)	90 Days (mm)	Percent Decrease Between With and Without SF 28-Day (%)	Percent Difference (%)
430-0.35	0.98	24.89		0.45	11.43		
SF 7.5% 430-0.35	0.17	4.32	83	0.09	2.29	80	47.06
430-0.45	1.29	32.77		0.74	18.80		
SF 7.5% 430-0.45	0.27	6.86	79	0.16	4.06	78	40.74
530-0.35	0.95	24.13		0.48	12.19		
SF 7.5% 530-0.35	0.18	4.57	81	0.11	2.79	77	38.89
530-0.45	1.23	31.24		0.72	18.29		
SF 7.5% 530-0.45	0.34	8.64	72	0.20	5.08	72	41.18

3.5.2 Influence of Water-To-Cementitious Materials Ratio on RMT Results

As can be observed from Tables 3.14 through 3.17, the w/cm impacts the RMT results by increasing the depth of chloride ion migration. Table 3.17 and Figure 3.5 show the RMT results for the first phase of the study grouped together by w/cm. An increase in w/cm from 0.35 to 0.45 resulted in increases in the migrated chloride ions by 41% and 57% for the 28-day and 90-day concrete samples, respectively.

Table 3. 17: Depth of Chloride Ion Migration in Phase 1 Concretes

Water to Cementitious Material Ratio (w/cm)	28 Days (in)	28 Days (mm)	90 Days (in)	90 Days (mm)	Percent Difference (%)
0.35	0.96	24.47	0.47	11.81	107.17
0.4	1.06	26.92	0.59	14.86	81.20
0.45	1.35	34.34	0.74	18.85	82.21

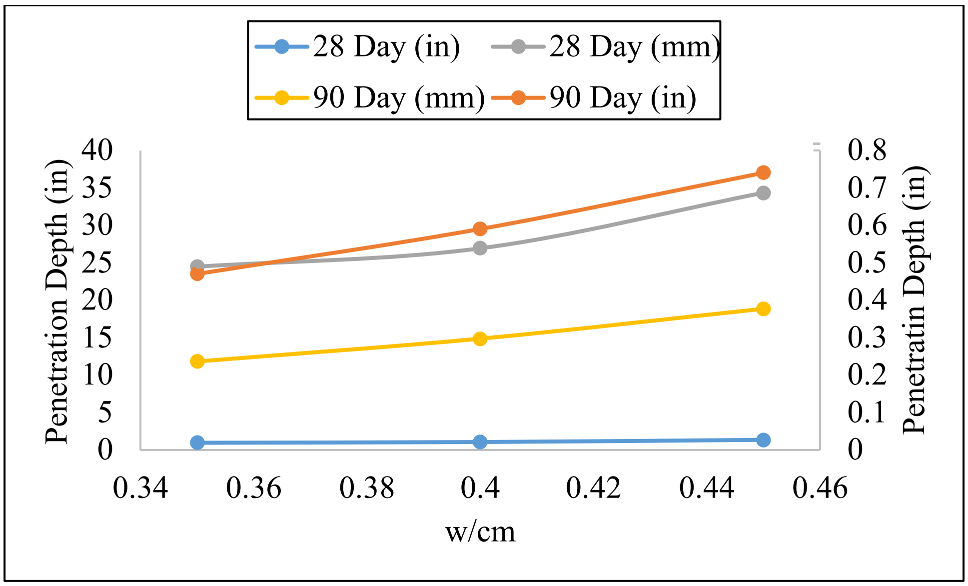

Figure 3. 5: RMT Results as Affected by Change in w/cm

3.6 Surface Resistivity Test (SRT) Results

As discussed earlier, surface resistivity is a test that utilizes a 4-pin Wenner probe that measures the surface resistivity of concrete. A number of State DOTs have incorporated the surface resistivity test and Wenner probe into their quality assurance tests of concrete. Each batch of concrete produced a total of seven 102 mm x 202 mm (4 in x 8 in) concrete cylinders which were tested with the Wenner probe. The following sections discuss the SRT results of the study. The impact of binder type and factor, curing age, and w/cm on SRT results are discussed and presented in the following sections. It was observed in the study that the increase of binder type and content and concrete age increased SRT readings, and higher w/cm adversely impacted SRT results. Appendix C will contain all the surface resistivity results from the study from all measurement periods.

3.6.1 Impact of Binder Content on SRT Results

The usage of various supplementary materials had an impact on the SRT results. Silica fume concrete samples had the highest SRT readings which means that the mixtures containing silica fume best resisted chloride ion penetration followed, by the slag concretes and then fly ash concretes. The performance ranking of the binders in the SRT was consistent to a study done by the Tennessee Technological University in 2015 (Eagan, 2015). The study by the Tennessee Technological University was only confined to SRT. In this study, it showed that, in general, binder improves the ability of concrete to resist the movement of chloride ions, thus the rebars inside the concrete will have increased protection against corrosion and enhanced longevity. The rest of this study was also consistent to those reported by the New Jersey Department of Transportation (Nassif, Rabie, Na, Salvador, 2015).

3.6.1.1 Impact of Cement Content on SRT Results

The impact of cement content on SRT readings are shown in the Table 3.18 and Figure 3.6 for the concretes without the use of SCMs. Table 3.19 depicts the SRT results from phase two of the study with a portion of Portland cement replaced by supplementary cementitious materials.

Table 3. 18: Average 28-Day and 90-Day SRT Results for Phase 1 Concretes

Cement Content (kg/m^3)	28 Days (kΩcm)	90 Days (kΩcm)	Percent Increase (%)
530	8.14	15.86	94.91
480	9.01	21.98	144.07
430	10.10	21.55	113.26
380	10.25	20.50	99.95
330	9.39	21.77	131.84

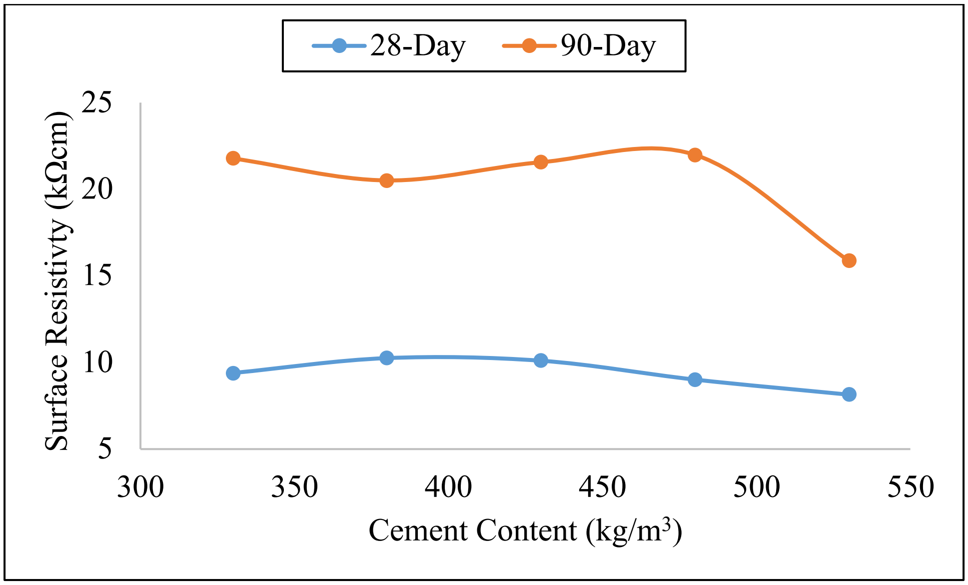

Figure 3. 6: Surface Resistivity vs. Cement Content with no SCMs

There's a little discrepancy in the 330 kg/m^3 (556 lb/yd^3) because there was only a single batch for this mixture. The other cement contents had between two to three batches, so the sample size for the cement content was larger than the single batch of the 330 kg/m^3 (556 lb/yd^3) concrete. Table 3.19 shows that there was a large percentage of increase in the SRT readings for fly ash concretes when concrete age was extended from 28 to 90 days. Overall, the SRT readings belonging to the fly ash concretes were lowest, whereas the silica fume concretes produced highest SRT results.

Table 3. 19: Average 28- and 90-Day SRT Results for Phase 2 Concretes

Cement Content with Replacement (kg/m^3-w/cm)	28 Days (kΩcm)	90 Days (kΩcm)	Percent Increase (%)
Slag 430-0.35	35.11	53.02	51.00
Slag 430-0.45	22.19	34.50	55.46
Slag 530-0.35	29.08	47.05	61.80
Slag 530-0.45	18.39	27.03	46.96
Fly Ash 430-0.35	26.15	95.65	265.71
Fly Ash 430-0.45	16.81	60.05	257.23
Fly Ash 530-0.35	22.39	63.69	184.41
Fly Ash 530-0.45	16.93	48.80	188.18
Silica Fume	71.09	117.66	65.52

3.6.1.2 Impact of Fly Ash on SRT Results

Table 3.20 presents the average 28- and 90-day SRT readings for the studied fly ash concretes. With increasing cement substitutions, the SRT readings also increased.

Table 3. 20: Average SRT Results for 28-Day and 90-Day Fly Ash Concretes

Cement Content with Replacement (kg/m^3-w/cm)	28 Days (kΩcm)	Percent Increase between with and without Fly Ash Mixture (%)	90 Days (kΩcm)	Percent Increase between with and without Fly Ash Mixture (%)	Percent Increase Between 28- and 90-Day Results (%)
430-0.35	13		32		
FA 15% 430-0.35	13	3	42	32	214
FA 30% 430-0.35	22	72	81	154	264
FA 45% 430-0.35	43	229	164	411	283
430-0.45	8		15		
FA 15% 430-0.45	10	24	30	102	205
FA 30% 430-0.45	14	79	53	255	272
FA 45% 430-0.45	26	227	97	543	269
530-0.35	11		23		
FA 15% 530-0.35	16	46	41	79	157
FA 30% 530-0.35	19	72	74	220	289
FA 45% 530-0.35	32	193	130	464	303
530-0.45	6		11		
FA 15% 530-0.45	8	36	23	113	188
FA 30% 530-0.45	20	235	43	288	113
FA 45% 530-0.45	23	276	80	630	256

Once fly ash replaced a portion of Portland cement by 15%, the SRT readings increased by 25 and 69% for the 28 and 90-day concretes. The increase in SRT results were 99 and 210% for the two ages, respectively, when fly ash substituted 30% by weight of Portland cement. The 45% Portland cement replacement resulted in the averagely increased SRT readings of nearly 226 and 481% for the 28- and 90-day fly ash concretes. On the average, 90-day SRT readings were larger than that of the 28-day samples by 188, 231, and 280% when fly ash substituted a portion of Portland cement by weight of 15, 30, and 45%.

The increase in the w/cm reduced the SRT results of the studied fly ash concretes. An increase in w/cm from 0.35 to 0.45 decreased SRT readings by averagely 29 and 39% for the 28- and 90-day fly ash concretes.

3.6.1.3 Impact of Slag on SRT Results

Table 3.21 (A and B) presents the average SRT results for the slag concretes. Fifteen percent replacement of Portland cement by slag increased the SRT by averages of 68 and 22% for the 28- and 90-day samples, respectively. These increases were 166 and 88% for the two concrete ages, respectively, when slag substituted 30% of cement weight. Once slag constituted 45% of the total binder, the increase in SRT readings were 294 and 188% for the slag concretes cured for 28 and 90 days, respectively. The increases in w/cm had an opposite effect on the SRT readings. When w/cm increased from 0.35 to 0.45, the SRT results decreased by 38 and 38% for the 28- and 90-day samples. An increase in the curing age from 28 to 90 days, increased the SRT readings by averagely 54, 51, and 56% for the binders consisted of 15, 30, and 45% slag, respectively. As discussed in this section and Section 3.6.1.2, concretes containing slag and fly ash had higher surface resistivity readings than the concretes without supplementary cementitious materials. However, concretes that contained slag had higher SRT readings than the equivalent fly ash concretes with the same amount of cement and w/cm.

Table 3. 21A: Average SRT Readings for 28-Day and 90-Day Slag Concretes

Cement Content with Replacement (kg/m^3-w/cm)	28 Day (kΩcm)	Percent Increase between with and without Slag Mixture 28-Day (%)	90 Day (kΩcm)	Percent Increase between with and without Slag Mixture 90-Day (%)	Percent Increase Between 28 and 90 Day Results (%)
430-0.35	13		32		
S 15% 430-0.35	21	61	35	8	66
S 30% 430-0.35	35	171	52	62	48
S 45% 430-0.35	50	285	72	126	45

Table 3. 21B: Average SRT Readings for 28-Day and 90-Day Slag Concretes

Cement Content with Replacement (kg/m^3-w/cm)	28 Day (kΩcm)	Percent Increase between with and without Slag Mixture 28-Day (%)	90 Day (kΩcm)	Percent Increase between with and without Slag Mixture 90-Day (%)	Percent Increase Between 28 and 90 Day Results (%)
430-0.45	8		15		
S 15% 430-0.45	13	58	19	25	48
S 30% 430-0.45	22	171	32	116	50
S 45% 430-0.45	32	303	52	249	62
530-0.35	11		23		
S 15% 530-0.35	20	81	30	32	53
S 30% 530-0.35	27	147	44	90	61
S 45% 530-0.35	40	266	67	192	67
530-0.45	6		11		
S 15% 530-0.45	11	77	15	36	41
S 30% 530-0.45	17	187	25	123	43
S 45% 530-0.45	27	356	42	278	52

3.6.1.4 Impact of Silica Fume on SRT Results

Table 3.22 documents the average SRT readings of concrete samples at the 28- and 90-day age for the silica fume concretes. When curing time was extended from 28 to 90 days, the SRT results of the studied silica fume concretes increased by 66%. An increase in water-to-cementitious materials ratio from 0.35 to 0.45 reduced SRT readings by nearly 52%. With only 7.5% by weight replacement of Portland cement, silica fume offered significantly higher SRT readings than fly ash and slag.

Table 3. 22: Average SRT Results for 28- and 90-Day Silica Fume Concretes

Cement Content with Replacement (kg/m^3-w/cm)	28 Days (kΩcm)	Percent Increase between with and without SF Mixture 28-Day (%)	90 Days (kΩcm)	Percent Increase between with and without SF Mixture 90-Day (%)	Percent Increase (%)
430-0.35	13		32		
SF 7.5% 430-0.35	99	662	171	434	72
430-0.45	8		15		
SF 7.5% 430-0.45	47	488	76	407	63
530-0.35	11		23		
SF 7.5% 530-0.35	91	727	149	539	63
530-0.45	6		11		
SF 7.5% 530-0.45	47	683	75	582	59

3.6.2 Influence of Age on SRT Results

Throughout the study, the impact of concrete age has always been positive for the results of RCPT, RMT, and SRT. The impact of age on increasing SRT readings was also reported in a study by the Kansas Department of transportation (KDOT) (Jenkins, 2015). In the KDOT study of surface resistivity, it was shown as concrete age increased so did the SRT readings. This trend remained intact irrespective of concrete constituents and proportions.

3.6.3 Influence of Testing Time on SRT Results

The time of when the surface resistivity reading was taken also impacted the results of the test. The initial reading was always the highest reading during the entire one-hour testing procedure. The surface resistivity reading intervals were at 0, 10, 20, 30, 40, and 60 minutes. In both phases of the study and for both 28- and 90-day concrete samples, the surface resistivity readings decreased as the time of reading increased. There were some readings in which there was a slight increase from the previous reading. The slight increase could have been attributed to the misplacement or slight movement of the device during measurement.

3.6.4 Influence of Water-to-Cementitious Materials Ratio on SRT Results

The increases of the w/cm tended to decrease the SRT readings. This trend can be seen throughout Tables 3.19 through 3.23. Table 3.23 shows the average SRT readings taken in the phase one of this study. A decrease of nearly 75% in SRT results was obtained when w/cm reduced from 0.45 to 0.35. Figure 3.7 shows the decrease in surface resistivity with the increase in w/cm.

Table 3. 23: Concretes without SCMs SRT Readings as Affected by w/cm

Water to Cementitious Material Ratio (w/cm)	28 Day (kΩcm)	90 Day (kΩcm)	Percent Increase (%)
0.35	12	30	150
0.4	9	20	117
0.45	8	16	102

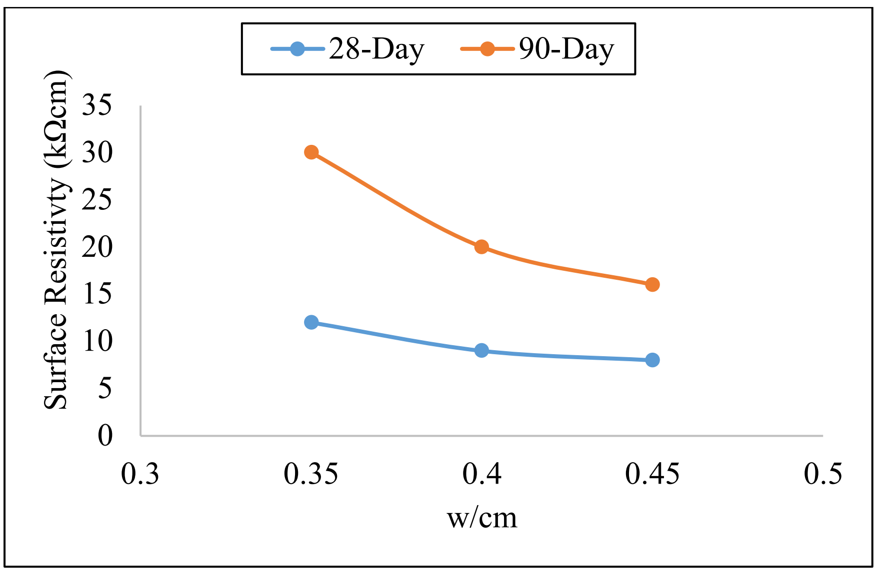

Figure 3. 7: Surface Resistivity vs. w/cm

3.7 Accelerated Corrosion Test (ACT) Results

The setup for the accelerated corrosion test was in accordance to FM 5-522. The corrosion samples were 102 mm x 152 mm (4 in x 6 in) cylindrical specimens. A Grade 60 12.7 mm (0.5 in) rebar was inserted in the middle of the specimens, and the specimens were submerged 76 mm (3 in) into a 5% NaCl salt water solution. A voltage of six volts was maintained throughout the study, and current readings were taken every 24-hours. The trend of the data shows that a higher amount of cement content increases the life span of concrete, whereas the increase of w/cm decreases the longevity of concrete specimen. A similar trend was observed in the samples with high percentages of supplementary cementitious materials; the higher amount of cement replaced by the SCMs the longer it took for test the samples to fail.

3.7.1 Impact of Binder Content on ACT Results

In both phases of the study, the high amount of binder content increased the number of days for the concrete samples to fail. The trend with respect to increased cement content was also noted in previous studies (Wee et. al., 1999) (Maler, 2017).

3.7.1.1 Impact of Cement Content on ACT Results

The impact of cement content was very relevant from the initial results of the study. Cement content increased the time it took for concrete samples to fail with or without supplementary cementitious materials. Table 3.24 shows the influence of the cement factor in the first phase of the study. As the cement increased the number of days until failure also increased. There was nearly 127% percent of increase in days to failure between the 330 kg/m^3 (556 lb/yd^3) and 480 kg/m^3 (809 lb/ft^3) cement content (from 37 days to 84 days). Additional increases in cement beyond 480 kg/m^3 (809 lb/ft^3) did not improve ACT results.

Table 3. 24: Average Corrosion Data for 28-Day Concretes without SCMs

Cement Content (kg/m^3)	Days Until Failure of 28 Day Samples
530	84
480	85
430	69
380	48
330	37

3.7.1.2 Impact of Fly Ash on ACT Results

Concrete samples lasted longer before failure with addition of fly ash. Table 3.25 presents the average corrosion data for the 28-day fly ash concretes. When fly ash replaced 15% by weight or Portland cement, the percent increase in the number of days to failure, as compared to that of the no-fly ash concrete, was about 29%. At 30 and 45% by weight placements of Portland cement, the increases in the ACT results were averagely 129% and 362%, respectively. An increase in the water-to-cementitious materials ratio had an adverse effect on ACT results. Once w/cm increased from 0.35 to 0.45, the number of days to failure reduced by nearly 24%.

Table 3. 25: Average Number of Days it Took for Fly Ash Concrete Samples to Fail

Cement Content with Replacement (kg/m^3-w/cm)	Days Until Failure of 28-Day Samples	Percent Increase Between Fly Ash and No SCM Mixtures
430-0.35	98	
FA 15% 430-0.35	124	27
FA 30% 430-0.35	205	109
FA 45% 430-0.35	366	273
430-0.45	41	
FA 15% 430-0.45	67	63
FA 30% 430-0.45	144	251
FA 45% 430-0.45	327	698
530-0.35	132	
FA 15% 530-0.35	148	12
FA 30% 530-0.35	249	89
FA 45% 530-0.35	371	181
530-0.45	43	
FA 15% 530-0.45	67	56
FA 30% 530-0.45	123	186
FA 45% 530-0.45	385	795

3.7.1.3 Impact of Slag on ACT Results

Incorporation of slag into the studied mixtures also increased the numbers of days to failure and the results are shown in Table 3.26. A 15% substitution of Portland cement by slag, resulted in an average increase of 82% in days to failure. Once slag replaced 30 and 45% by weight of Portland cement, the increases in days to failure were approximately 61 and 265%, respectively. An increase of w/cm resulted in the reduced ACT results. A change in w/cm from 0.35 to 0.45, decreased number of days to failure by 23%. Overall, slag concretes did show better performance in accelerated corrosion test than the equivalent concretes containing fly ash.

Table 3. 26: Average Number of Days it Took for Slag Concretes to Fail

Cement Content with Replacement (kg/m^3-w/cm)	Days Until Failure of 28 Day Samples	Percent Increase Between Fly Ash and No SCM Mixture
430-0.35	98	
S 15% 430-0.35	99	1
S 30% 430-0.35	136	39
S 45% 430-0.35	282	188
430-0.45	41	
S 15% 430-0.45	59	44
S 30% 430-0.45	108	163
S 45% 430-0.45	221	439
530-0.35	132	
S 15% 530-0.35	88	-33
S 30% 530-0.35	172	30
S 45% 530-0.35	327	148
530-0.45	43	
S 15% 530-0.45	54	26
S 30% 530-0.45	90	109
S 45% 530-0.45	317	637

3.7.1.4 Impact of Silica Fume on ACT Results

Out of the three supplementary cementitious materials used in this study, silica fume concrete performed better than concretes containing fly ash and slag. It was very evident during the study that the silica fume concrete samples did not show any sign of failure until very late in the study. It took approximately a year until there was any signs of failure from the four groups of silica fume concretes. With only 7.5% of cement replaced with silica fume, all silica fume concretes had over 300 days before failure. Table 3.27 presents the results of the accelerated corrosion test for the studied silica fume concretes. An increase in w/cm from 0.35 to 0.45 reduced the number of days before failure by averagely 3%.

Table 3. 27: Average Number of Days it took for Silica Fume Concretes Samples to Fail

Cement Content with Replacement (kg/m^3-w/cm)	Days Until Failure of 28 Day Samples	Percent Increase Between Silica Fume and No SCM Mixture
430-0.35	98	
SF 7.5% 430-0.35	342	249
430-0.45	41	
SF 7.5% 430-0.45	329	702
530-0.35	132	
SF 7.5% 530-0.35	368	179
530-0.45	43	
SF 7.5% 530-0.45	358	732

3.7.2 Influence of Water-to-Cementitious Material Ratio on ACT Results

The influence of w/cm was also very prominent in the accelerated corrosion test. As shown on Tables 3.25 through 3.27, the decrease in w/cm resulted in the increase in the number of days to failure when results were compared to that of the concretes with the same amount of cement replacement and cement content.

Chapter 4 - Statistical Analysis of Test Results

4.1 - Background on Statistical Analysis

Statistical analyses were conducted to ascertain the influential variables affecting results of RCPT, RMT, SRT, and ACT; and the relationship amongst them. A statistical software called "Stata" was utilized to analyze the measured results from all the chloride ion penetrability methodologies employed in this study. The Stata software package was pre-installed with a multitude of statistical models. Once the data from the tests were loaded into the software, the independent and dependent variables were selected. Due to the interval nature of the outcome variables, it was determined that the linear regression model was the best suite. Various other models were also used to examine the results, but they were found to be unsuitable.

A t-test was also performed on the results of the four different tests to determine if there was any significant difference to the base conditions. The t-test was done similarly to the linear regression model: first the data was loaded into the software, independent and dependent variables were set, then a summary table after completion of the t-test analysis was completed.

Three explanatory variables were analyzed within the four adopted tests: binder content, w/cm, and concrete age. Stata analyzed the results from the tests by comparing the data to the base conditions of 430 kg/m^3 (725 lb/yd^3) binder content, 28-day concrete age, and 0.35 w/cm. In this study, the original lowest categories of binder content 330 kg/m^3 (556 lb/yd^3) and 380 kg/m^3 (641 lb/yd^3), as well as w/cm of 0.4 had small number of data points which would had caused inconclusive statistical results if used as based conditions. Once the program completed analyzing the data, a summary table displayed the results of the test. All analyses were done at a 95% confidence interval.

4.2 Factors That Impacted the Test Results

As mentioned in the previous section, there were three variables; binder content, concrete age, and water-to-cementitious materials ratio that were used for statistical analysis. All the results from the four tests were analyzed to the base binder content, concrete age, and w/cm conditions as mentioned in the Section 4.1. The base conditions were set as a point of reference for all the other data, thus any deviation from the base conditions could be accounted for with the aid of the software. Both the t-test and linear regression were set to analyze the data at a 95% confidence level. The impact of concrete age, binder content, and w/cm on the test results are discussed in the sections to follow. In general, statistical analyses of the test results revealed that w/cm and concrete age had significant influence on the results of RCPT, RMT and SRT. While binder content was considered as a control variable, it showed statistically insignificant to the results of the RCPT, RMT, ACT, and SRT.

4.2.1 Factors Affecting RCPT Results

Table 4.1 summarizes the analyses of RCPT results and their statistical relevancies. According to Table 4.1, influence of w/cm and curing age impacted the RCPT results the most. When the role of the binder content was analyzed, it was determined that the binder content did not have a significant impact as the concrete age and w/cm had. The linear model analysis conducted at the 95% confidence level showed that the higher w/cm generally increased the coulombs, while RCPT results decreased when concrete age was extended from 28 to 90 days. The tables presented in the Section 3.4; Tables 3.6 through 3.11, showed that the increased w/cm and concrete age inversely impacted the RCPT results. The proposed model also showed that the w/cm played a major influence on the amount of RCPT values. As reported in the Section 3.4.2, an increase in concrete age caused the RCPT results to decrease, which was mirrored by the results of the statistical analysis of the RCPT data.

Table 4. 1: Statistical Analysis of RCPT Results

Number of observations = 64						
F(3, 60) = 7.80						
Prob > F = 0.0002						
R-squared = 0.2807						
Adj R-squared = 0.2447						
Root MSE = 1066						
RCPT	Coef.	Std. Error	t	P>t	[95% Conf. Interval]	
Binder 530	348.24	266.64	1.31	0.20	-185.12	881.60
w/cm 0.45	729.66	266.90	2.73	0.01	195.77	1263.54
Age 90	-990.20	266.64	-3.70	0.00	-1523.56	-456.83
Constants	1376.68	268.72	5.12	0.00	839.15	1914.20

4.2.2 Factors Affecting RMT Results

The impact of w/cm and curing age was also more statistically significant on the RMT results, whereas binder content was not statistically significant. Table 4.2 presents the findings associated with the statistical analyses of the RMT data at the 95% confidence interval. The analysis of the RMT results showed that the depth of chloride migration decreased as the concrete age increased. The statistical analysis based on w/cm factor was also consistent with the results of the study reported in Section 3.4.3. Similar to the RCPT results, the binder content did not have a statistically significant impact on the RMT results.

4.2.3 Factors Affecting ACT Results

The age of the concrete samples used for the accelerated corrosion study was 28 days. Table 4.3 summarizes the results of the statistical analysis for the ACT measurements. The statistical analyses of the ACT results revealed to be similar to those of RMT and RCPT as the binder content did not have any statistically significant impact on the ACT results. Water-to-cementitious materials ratio had statistically weak correlation with the number of days before failure occurred.

Table 4. 2: Statistical Analysis of RMT Results

Number of observations = 64						
F(3, 60) = 11.35						
Prob > F = 0.0000						
R-squared = 0.3621						
Adj R-squared = 0.3302						
Root MSE = 6.1236						
RMT_mm	Coef.	Std. Err.	t	P>t	[95% Conf. Interval]	
Binder 530	0.16	1.53	0.11	0.91	-2.89	3.23
w/cm 0.45	3.72	1.53	2.43	0.02	0.66	6.78
Age 90	-8.12	1.53	-5.30	0.00	-11.18	-5.06
Constant	14.31	1.53	9.35	0.00	11.24	17.37

Table 4. 3: Statistical Analysis of ACT Results

Number of observations = 32						
F(2, 29) = 0.80						
Prob > F = 0.4604						
R-squared = 0.0521						
Adj R-squared = - 0.0133						
Root MSE = 120.28						
Corrosion	Coef.	Std. Err.	t	P>t	[95% Conf. Interval]	
Binder 530	22.06	0.52	0.52	0.61	-64.91	109.04
w/cm 0.45	-48.93	-1.15	-1.20	0.26	-135.91	38.039
Constant	208.16	35.83	5.65	0.00	132.83	283.48

4.2.4 Factors Affecting SRT Results

Table 4.4 presents the results of the statistical analysis for the surface resistivity data performed at the confidence level of 95%. The impact of curing age was consistent with the results reported in the Section 3.6. Both w/cm and concrete age had the profound influence on SRT results, whereas the binder content showed the contrary.

Table 4. 4: Statistical Analysis of SRT Results

Number of observations = 64						
F(3, 60) = 8.64						
Prob > F = 0.0001						
R-squared = 0.3017						
Adj R-squared = 0.2668						
Root MSE = 32.812						
Surface Resistivity	Coef.	Std. Err. t	t	P>t	[95% Conf. Interval]	
Binder 530	-6.36	8.20	-0.80	0.44	-22.78	10.05
w/cm 0.45	-22.24	8.22	-2.70	0.01	-38.67	-5.8
Age 90	34.21	8.21	4.17	0.00	17.80	50.64
Constant	42.67	8.27	5.16	0.00	26.15	59.21

4.3 Relationship between SRT and RCPT

Figures 4.1 and 4.2 present the relationship between SRT and RCPT for the studied 28- and 90-day concretes, respectively. Figure 4.3 shows the relationship between the independent and dependent variable for the combined 28- and 90-day concretes. The predictive RCPT results shown in these figures are obtained by substituting experimental SRT measurements in the proposed equations. As can be seen, there is a clear inverse relationship between RCPT, as a dependent variable and SRT as an independent variable. The proposed equations at different concrete ages represent the most suitable relationship between independent and dependent variable. A similar trend also reported by the Missouri Department of Transportation (MoDOT) (Keven, Halmen, Hudson, 2015). Other studies that also compared the results between the SRT and RCPT also had similar results of the inverse relationship between the two variables (Smith, 2006) (Ryan, 2011) (Shahroodi, 2010).

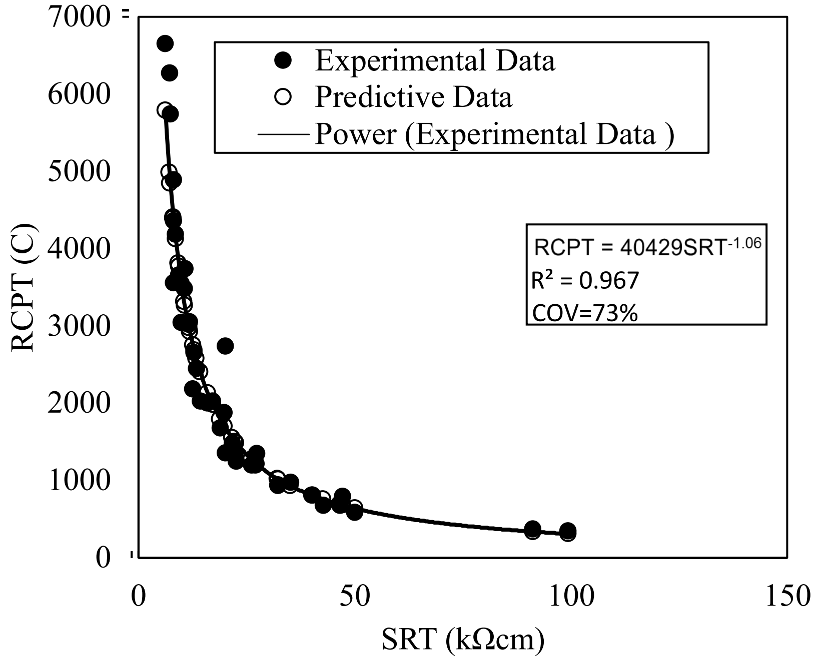

Figure 4. 1: 28-Day RCPT vs. SRT

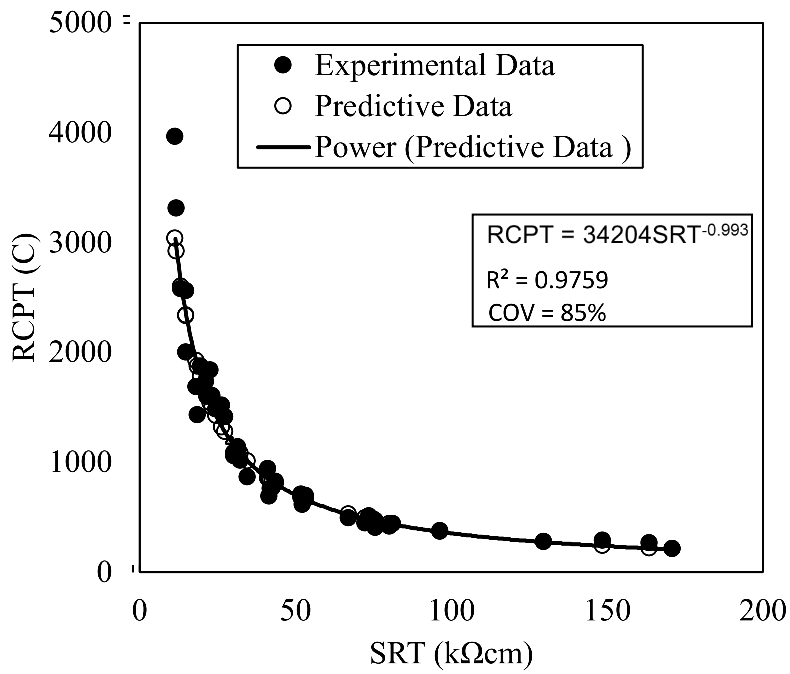

Figure 4. 2: 90-Day RCPT vs. SRT

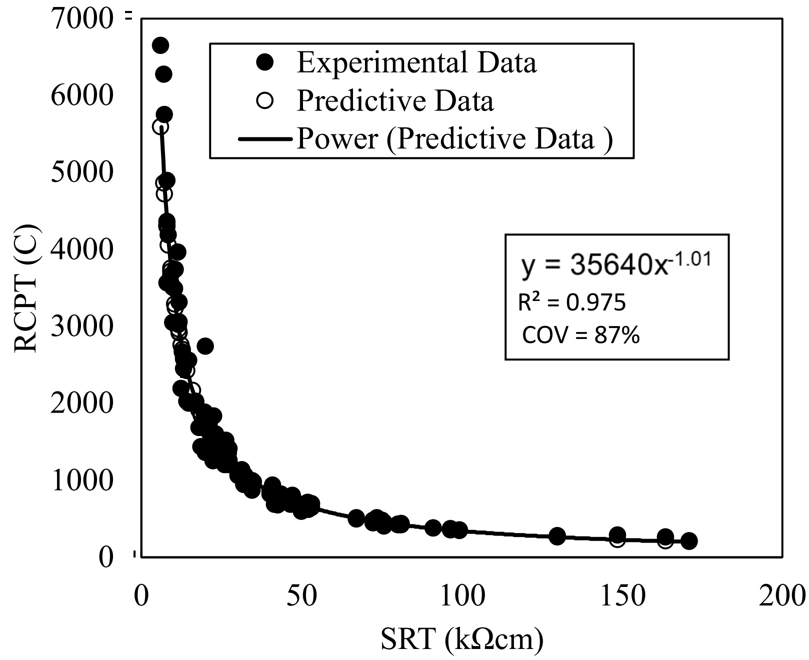

Figure 4. 3: Combined 28-and 90-Day SRT vs. RCPT

Table 4.5 shows the comparison between experimental data and predictive RCPT results from the 28-and 90-day concretes. Table 4.5 also compares the 28-day RCPT obtained through proposed equation of this study to the RCPT values derived from equations proposed by other State DOTs. The RCPT results in this study were for the most part comparable to those of MoDOT, KDOT, LaDOTD, and NJDOT. However, RCPT values of the FDOT were found to be higher than the rest. Table 4.6 (A and B) documents the 90-day experimental and predictive RCPT values obtained this study.

Table 4. 5: 28-Day RCPT Results Compared with Predictive Results from Other State DOTs

Mixture ID	Exp. SRT	Exp. RCPT	Predictive RCPT	Percent Difference Between Experimental RCPT and Predictive RCPT	RCPT of MoDOT	RCPT of KDOT	RCPT of NJDOT	RCPT of LaDOTD	RPCT of FDOT
530-0.35	11	3738	3183	16	3372	3122	2525	3083	5867
480-0.35	12	3022	2902	4	3090	2870	2344	2839	5308
430-0.35	13	2658	2666	0	2852	2657	2189	2633	4840
530-0.40	7	5745	5139	11	5306	4831	3716	4723	9875
430-0.40	9	3660	3937	7	4124	3790	2998	3725	7393
480-0.40	8	4359	4461	2	4641	4246	3315	4164	8467
380-0.40	12	3050	2902	5	3090	2870	2344	2839	5308
530-0.45	6	6648	6051	9	6194	5607	4240	5463	11794
480-0.45	7	6274	5139	20	5306	4831	3716	4723	9875
430-0.45	8	4887	4461	9	4641	4246	3315	4164	8467
380-0.45	9	4187	3937	6	4124	3790	2998	3725	7393
330-0.45	9	3562	3937	10	4124	3790	2998	3725	7393
FA 15% 430-0.35	13	2446	2580	5	2765	2578	2132	2557	4670
FA 30% 430-0.35	22	1347	1504	11	1659	1577	1380	1581	2598
FA 45% 430-0.35	43	675	755	11	864	841	791	856	1228
FA 15% 430-0.45	10	3047	3544	15	3733	3443	2754	3392	6594
FA 30% 430-0.45	14	2025	2405	17	2587	2418	2014	2402	4326
FA 45% 430-0.45	26	1196	1270	6	1414	1352	1204	1360	2162
FA 15% 530-0.35	16	2001	2134	6	2310	2169	1829	2159	3800
FA 30% 530-0.35	19	1678	1789	6	1955	1847	1587	1846	3138
FA 45% 530-0.35	32	943	1019	8	1148	1106	1008	1118	1703
FA 15% 530-0.45	8	3557	4385	21	4567	4181	3270	4101	8311
FA 30% 530-0.45	20	2740	1681	48	1843	1745	1509	1746	2932
FA 45% 530-0.45	23	1249	1485	17	1639	1559	1366	1563	2562
S 15% 430-0.35	21	1358	1613	17	1772	1680	1460	1683	2803
S 30% 430-0.35	35	973	928	5	1050	1015	934	1028	1537
S 45% 430-0.35	50	588	639	8	738	723	692	738	1025
S 15% 430-0.45	13	2188	2754	23	2940	2736	2247	2710	5013
S 30% 430-0.45	22	1479	1549	5	1706	1620	1413	1623	2683
S 45% 430-0.45	32	937	1017	8	1146	1104	1006	1116	1698
S 15% 530-0.35	20	1878	1701	10	1864	1763	1523	1764	2969
S 30% 530-0.35	27	1198	1222	2	1363	1305	1167	1314	2073
S 45% 530-0.35	40	815	805	1	918	892	833	906	1317
S 15% 530-0.45	11	3484	3310	5	3500	3236	2607	3192	6123
S 30% 530-0.45	17	2024	1979	2	2151	2025	1722	2019	3501
S 45% 530-0.45	27	1345	1211	10	1352	1294	1159	1304	2053
SF 7.5% 430-0.35	99	347	309	12	371	373	385	386	465
SF 7.5% 430-0.45	47	682	689	1	793	774	735	789	1113
SF 7.5% 530-0.35	91	374	338	10	404	405	414	419	513
SF 7.5% 530-0.45	47	796	679	16	782	764	727	779	1095

Table 4. 6A: 90-Day RCPT Results Compared with Predictive Results

Mixture ID	Exp. SRT	Exp. RCPT	Predictive RCPT	Percent Difference Between Experimental RCPT and Predictive RCPT
530-0.35	23	1834	1520	19
480-0.35	27	1407	1296	8
430-0.35	32	1135	1095	4
530-0.40	13	2571	2679	4
430-0.40	18	1685	1939	14
480-0.40	27	1512	1296	15
380-0.40	21	1730	1664	4
530-0.45	11	3962	3162	22
480-0.45	12	3309	2900	13
430-0.45	15	2557	2324	10
380-0.45	20	1871	1746	7
330-0.45	22	1596	1589	0
FA 15% 430-0.35	42	755	767	2
FA 30% 430-0.35	81	437	383	13
FA 45% 430-0.35	164	261	182	36
FA 15% 430-0.45	30	1081	1099	2
FA 30% 430-0.45	53	693	601	14
FA 45% 430-0.45	97	370	317	16
FA 15% 530-0.35	41	936	789	17
FA 30% 530-0.35	74	506	422	18
FA 45% 530-0.35	130	274	232	17
FA 15% 530-0.45	23	1599	1430	11
FA 30% 530-0.45	43	762	756	1
FA 45% 530-0.45	80	413	387	6
S 15% 430-0.35	35	864	933	8
S 30% 430-0.35	52	704	613	14
S 45% 430-0.35	72	445	434	2
S 15% 430-0.45	19	1429	1815	24
S 30% 430-0.45	32	1014	1011	0
S 45% 430-0.45	52	614	609	1
S 15% 530-0.35	30	1055	1099	4
S 30% 530-0.35	44	820	732	11
S 45% 530-0.35	67	488	469	4

Table 4. 6B: 90-Day RCPT Experimental Results Compared with Predictive Results

Mixture ID	Exp. SRT	Exp. RCPT	Predictive RCPT	Percent Difference Between Experimental RCPT and Predictive RCPT
S 15% 530-0.45	15	1997	2302	14
S 30% 530-0.45	25	1479	1358	9
S 45% 530-0.45	42	687	777	12
SF 7.5% 430-0.35	171	212	174	20
SF 7.5% 430-0.45	76	400	410	3
SF 7.5% 530-0.35	149	285	201	35
SF 7.5% 530-0.45	75	475	416	13

4.4 Relationship between SRT and RMT

The relationship between SRT and RMT was also found to be inverse. If the SRT measurement increased or decreased, the RMT measurement showed opposite trends. Figure 4.5 and 4.6 presents the correlations between SRT and RMT for the 28- and 90-day concretes, respectively.

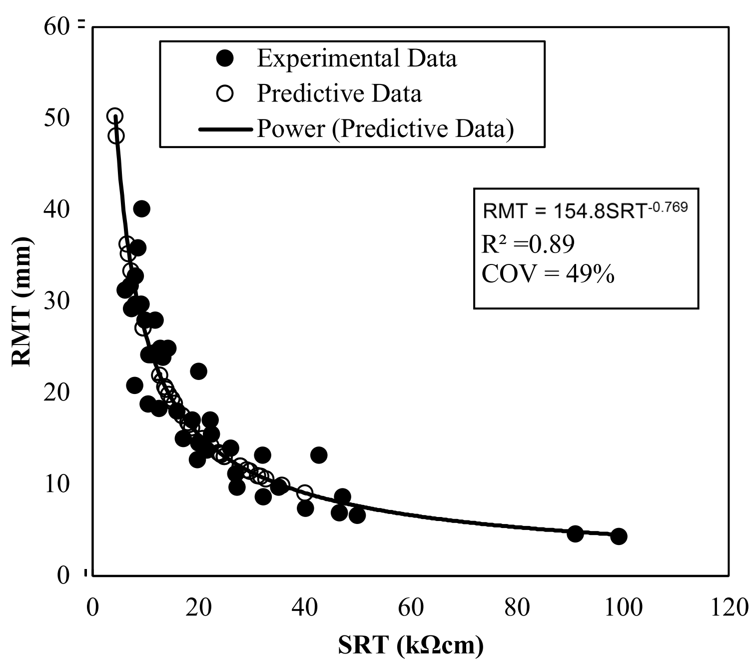

Figure 4. 4: 28-Day RMT vs. SRT

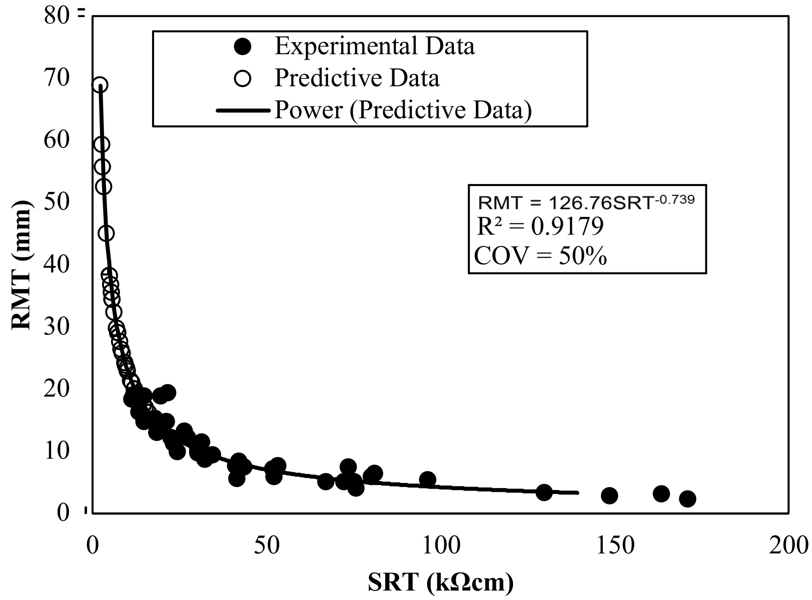

Figure 4. 5: 90-Day RMT vs. SRT

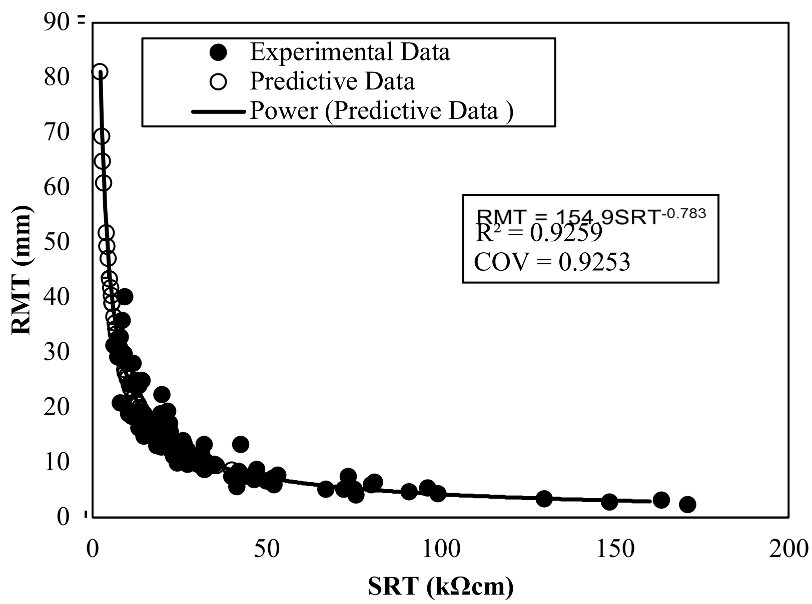

Figure 4. 6: Combined 28- and 90-Day SRT vs. RMT

Tables 4.7 (A and B) and 4.8 (A and B) present the experimental and predictive RMT results. The predictive results were obtained from using equations in the Figures 4.4 and 4.5. It can be observed that the predicted RMT measurements are for the most part in agreement with the experimental data.

Table 4. 7A: 28-Day Experimental and Predictive RMT Results

Mixture ID	Experimental SRT	Experimental RMT (mm)	Predictive RMT (mm)	Percent Difference Between Experimental RCPT and Predictive RCPT
530-0.35	11	24.13	25	3
480-0.35	12	24.38	23	4
430-0.35	13	24.89	22	14
530-0.40	7	29.21	33	13
430-0.40	8	20.83	31	39
480-0.40	9	29.72	28	6
380-0.40	12	27.94	23	19
530-0.45	6	31.24	38	19
480-0.45	7	31.75	34	7
430-0.45	8	32.77	31	6
380-0.45	9	35.81	30	19
330-0.45	9	40.13	28	37
FA 15% 430-0.35	13	23.88	21	13
FA 30% 430-0.35	22	17.02	14	18
FA 45% 430-0.35	43	13.21	9	42
FA 15% 430-0.45	10	27.94	26	5
FA 30% 430-0.45	14	24.89	20	22
FA 45% 430-0.45	26	13.97	13	10
FA 15% 530-0.35	16	18.03	18	2
FA 30% 530-0.35	19	17.02	16	5
FA 45% 530-0.35	32	13.21	11	21
FA 15% 530-0.45	8	29.72	31	4
FA 30% 530-0.45	20	22.35	15	37
FA 45% 530-0.45	23	15.49	14	9
S 15% 430-0.35	21	14.48	15	3
S 30% 430-0.35	35	9.65	10	4
S 45% 430-0.35	50	6.6	8	15
S 15% 430-0.45	13	18.29	22	19
S 30% 430-0.45	22	13.72	15	6
S 45% 430-0.45	32	8.64	11	21
S 15% 530-0.35	20	12.7	16	20
S 30% 530-0.35	27	11.18	12	9
S 45% 530-0.35	40	7.37	9	20
S 15% 530-0.45	11	18.8	25	29
S 30% 530-0.45	17	14.99	17	15
S 45% 530-0.45	27	9.65	12	23

Table 4. 7B: 28-Day Experimental and Predictive RMT Results

Mixture ID	Experimental SRT	Experimental RMT (mm)	Predictive RMT (mm)	Percent Difference Between Experimental RCPT and Predictive RCPT
SF 7.5% 430-0.35	99	4.32	5	4
SF 7.5% 430-0.45	47	6.86	8	16
SF 7.5% 530-0.35	91	4.57	5	5
SF 7.5% 530-0.45	47	8.64	8	8

Table 4. 8A: 28-Day Experimental and Predictive RMT Results

Mixture ID	Experimental SRT	Experimental RMT (mm)	Predictive RMT (mm)	Percent Difference Between Experimental RCPT and Predictive RCPT
530-0.35	22.7	12.19	12	4
480-0.35	27.49	12.19	10	17
430-0.35	31.52	11.43	9	21
530-0.40	13.41	16.26	17	5
430-0.40	26.54	13.21	11	23
480-0.40	18.15	15.24	14	10
380-0.40	21.35	14.73	12	18
530-0.45	11.47	18.29	19	4
480-0.45	11.93	19.05	19	3
430-0.45	14.97	18.8	16	18
380-0.45	19.66	18.8	13	37
330-0.45	21.77	19.3	12	46
FA 15% 430-0.35	42	8.38	8	10
FA 30% 430-0.35	81	6.35	5	29
FA 45% 430-0.35	164	3.05	3	5
FA 15% 430-0.45	30	1.02	10	162
FA 30% 430-0.45	53	7.62	6	17
FA 45% 430-0.45	97	5.33	4	24
FA 15% 530-0.35	41	7.62	8	1
FA 30% 530-0.35	74	7.37	5	37

Table 4. 8B: 90-Day Experimental and Predictive RMT Results

Mixture ID	Experimental SRT	Experimental RMT (mm)	Predictive RMT (mm)	Percent Difference Between Experimental RCPT and Predictive RCPT
FA 45% 530-0.35	130	3.3	3	3
FA 15% 530-0.45	23	11.18	11	3
FA 30% 530-0.45	43	7.87	7	5
FA 45% 530-0.45	80	5.84	5	20
S 15% 430-0.35	35	9.4	9	9
S 30% 430-0.35	52	7.11	7	9
S 45% 430-0.35	72	5.08	5	2
S 15% 430-0.45	19	12.95	13	4
S 30% 430-0.45	32	8.64	9	5
S 45% 430-0.45	52	5.84	6	11
S 15% 530-0.35	30	9.65	10	0
S 30% 530-0.35	44	7.37	7	0
S 45% 530-0.35	67	5.08	5	7
S 15% 530-0.45	15	14.73	16	7
S 30% 530-0.45	25	9.91	11	11
S 45% 530-0.45	42	5.59	8	31
SF 7.5% 430-0.35	171	2.29	3	20
SF 7.5% 430-0.45	76	4.06	5	20
SF 7.5% 530-0.35	149	2.79	3	10
SF 7.5% 530-0.45	75	5.08	5	1

4.5 Relationship between SRT and ACT

Overall, the most suitable relationship between SRT and ACT seems to be logarithmic. Figure 4.7 plots the measurements from both phases of the study. Figure 4.7 documents the relationship between ACT and SRT results obtained from the studied 28-day concretes.

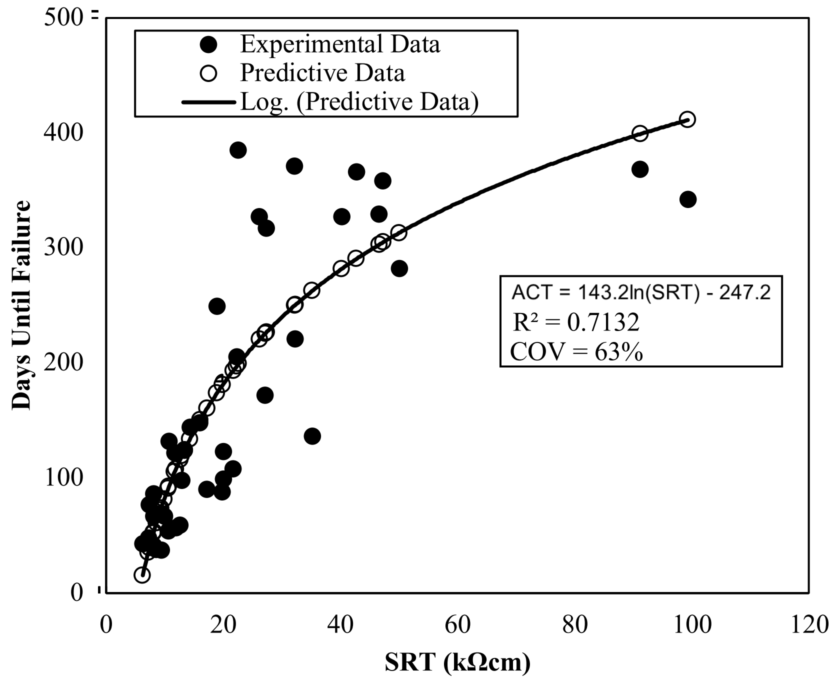

Figure 4. 7: Combined ACT and SRT Values

Chapter 5 - Conclusions

The goal of this study was to determine the effectiveness of SRT for concrete quality assurance and to evaluate the relationship between SRT and the three chloride ion ingress methods currently used by various State DOTs. Additionally, the influence of binder type and content, concrete age, and water-to cementitious materials ratio on the experimental results were also examined.

In this study, Type V Portland and three SCMs; namely fly ash, slag, and silica fume were used. Fine and coarse aggregates were supplied by a local quarry. To evaluate the transport properties of the studied concretes, RMT, RCPT, and ACT were employed. The evaluation of experimental results were based on binder content, binder type, w/cm, and concrete age.

The following sections reports on the conclusions of this study for each adopted testing program.

5.1 Conclusions on the Results of Individual Test

The SRT test has proven to be a consistent and viable testing method for concrete quality assurance. The usage of various binder types and factors did have a positive impact on SRT results. The increases in the binder content caused SRT readings to increase. The studied concretes containing SCMs produced superior SRT readings as compared to those offered by the mixtures without SCMs.

Increases in w/cm decreased the SRT readings, whereas increases in the concrete age produced higher SRT results for all studied concretes. The RCPT test results were also similarly affected by the concrete age, and binder type and content of the studied mixtures. Increase in concrete age improved RCPT values, whereas higher w/cm was detrimental to the RCPT values. The higher RCPT values makes concrete more susceptible to chloride ion penetrability. The use of SCMs decreased the RCPT values and the reductions were more pronounced as the replacement percentage of Portland cement by the SCMs increased. Amongst the three SCMs types utilized in this study, the silica fume produced the lowest RCPT values, whereas slag concretes reduced RCPT results better than the companion mixtures containing fly ash.

The results of the RMT as affected by the w/cm, binder content and type, and concrete age was similar to those of the RCPT. The depth of chloride ion migration decreased through increases in cement content and the SCMs replacing a portion of Portland cement. An opposite trend was found with increases in the w/cm as the depth of migrated chloride ions increased. Once concrete age increased from 28 to 90 days, the depth of migrated chloride ion decreased. The increase in binder content also decreased the depth of migrated chloride ions as well. Similar to the RCPT results, the inclusion of silica fume produced the smallest depth of migrated chloride ions in concrete.

The number of days it took for the ACT concrete samples to fail were also directly impacted by the binder content and w/cm. The higher amount of binder content increased the time to failure. On the other hand, the increase in w/cm decreased the numbers of days before failure occurred. While increases in the use of the three SCMs types increased the number of days to failure, as compared to that of concretes without SCMs, silica fume produced the best results. Slag concrete was more effective in increasing the number of days before failure than fly ash concrete.

Overall, amongst the three SCMs used in this study, silica fume produced the best results for the SRT, RCPT, ACT, and RMT. Slag concretes was more effective than fly ash concretes in reductions of RCPT and RMT results and increases in SRT and ACT values.

5.2 Relationship Between Concrete SRT and Transport Properties

The relationship between SRT and the three chloride ion ingress methods were determined to be inverse. The proposed predictive equations were found to be most suitable, and the comparisons between predictive and experimental values were in agreement. The results obtained from the adopted experimental program of this study indicate that the SRT can be used as an effective tool for concrete quality assurance, and to obtain concrete transport properties values based on the proposed statistical correlations.

Appendix A - Rapid Chloride Permeability Test (RCPT) Results

430 - 0.35

28 D (C)	90 D (C)
2275	1180
2776	1075
2922	1402
	1151

480 - 0.35

28 D (C)	90 D (C)
2411	1333
3228	1548
3428	1475
	1412

530 - 0.35

28 D (C)	90 D (C)
2878	1989
4408	1789
3929	1725

380 - 0.40

28 D (C)	90 D (C)
3049	1673
3047	1818
3053	1787

480 - 0.40

28 D (C)	90 D (C)
4332	1333
4408	1548
4336	1475

430 - 0.40

28 D (C)	90 D (C)
3321	1476
3774	1707
3885	1873

530 - 0.40 2nd

28 D (C)	90 D (C)
5209	2250
5882	2880
6143	2584

330 - 0.45

28 D (C)	90 D (C)
3329	1563
3667	1842
3690	1629

380 - 0.45

28 D (C)	90 D (C)
3962	1853
4066	2010
4534	1750

430 - 0.45

28 D (C)	90 D (C)
4452	2633
5079	2412
5129	2625

480 - 0.45

28 D (C)	90 D (C)
5672	3321
7679	3084
5470	3521

530 - 0.45

28 D (C)	90 D (C)
6120	4033
6732	4016
7093	3970
	3828

1. FA 15% 430-0.35		3. FA 30% 430-0.35		25. FA 45% 430-0.35	
28 D (C)	90 D (C)	28 D (C)	90 D (C)	28 D (C)	90 D (C)
1715	723	1344	493	828	224
2294	768	1398	391	658	326
2598	775	1299	427	692	234

2. FA 15% 430-0.45		4. FA 30% 430-0.45		26. FA 45% 430-0.45	
28 D (C)	90 D (C)	28 D (C)	90 D (C)	28 D (C)	90 D (C)
2543	1038	1846	575	1240	364
3008	1124	2071	710	1221	353
3086	870	2159	795	1127	393

5. FA 15% 530-0.35		7. FA 30% 530-0.35		27. FA 45% 530-0.35	
28 D (C)	90 D (C)	28 D (C)	90 D (C)	28 D (C)	90 D (C)
1996	950	2036	507	1076	263
2107	849	1585	504	834	280
1899	1008	1770	605	919	278

6. FA 15% 530-0.45		8. FA 30% 530-0.45		28. FA 45% 530-0.45	
28 D (C)	90 D (C)	28 D (C)	90 D (C)	28 D (C)	90 D (C)
4456	1853	2443	717	1209	387
3551	1345	3101	795	1200	446
3563		2675	773	1338	406

9. S 15% 430-0.35		11. S 30% 430-0.35		21. S 45% 430-0.35	
28 D (C)	90 D (C)	28 D (C)	90 D (C)	28 D (C)	90 D (C)
1338	864	962	730	577	450
1263	1096	1017	632	599	363
1473	864	940	677	701	440

10. S 15% 430-0.45		12. S 30% 430-0.45		22. S 45% 430-0.45	
28 D (C)	90 D (C)	28 D (C)	90 D (C)	28 D (C)	90 D (C)
2165	1388	1249	958	1088	641
2088	1469	1753	803	856	586
2311	1986	1436	1070	867	792

13. S 15% 530-0.35		15. S 30% 530-0.35		24. S 45% 530-0.35	
28 D (C)	90 D (C)	28 D (C)	90 D (C)	28 D (C)	90 D (C)
1841	894	1039	908	796	553
1823	1181	1326	691	878	495
1971	1090	1229	861	833	481

14. S 15% 530-0.45		16. S 30% 530-0.45		23. S 45% 530-0.45	
28 D (C)	90 D (C)	28 D (C)	90 D (C)	28 D (C)	90 D (C)
3100	2102	2025	1472	1563	823
3868	2066	2575	1142	1055	589
4101	1823	2022	1823	1418	650

17. SF 7.5% 430-0.35		18. SF 7.5% 430-0.45		19. SF 7.5% 530-0.35	
28 D (C)	90 D (C)	28 D (C)	90 D (C)	28 D (C)	90 D (C)
324	212	685	403	377	379
357	209	665	410	324	244
360	214	696	386	371	325

20. SF 7.5% 530-0.45	
28 D (C)	90 D (C)
776	472
816	477
601	526

Appendix B - Rapid Chloride Migration Test (RMT) Results

430 - 0.35		480 - 0.35		530 - 0.35	
28 D (in)	90 D (in)	28 D (in)	90 D (in)	28 D (in)	90 D (in)
0.99	0.44	0.95	0.47	0.92	0.47
0.97	0.42	0.96	0.51	0.97	0.48
1.01	0.45	0.91	0.48	1.00	0.50
	0.45		0.49		

430 - 0.40		480 - 0.40		530 - 0.40 \ 2nd	
28 D (in)	90 D (in)	28 D (in)	90 D (in)	28 D (in)	90 D (in)
1.17	0.53	0.80	0.55	1.18	0.62
1.19	0.61	0.80	0.53	1.22	0.61
1.14	0.58	0.85	0.52	1.12	0.69

330 - 0.45		380 - 0.45		430 - 0.45	
28 D (in)	90 D (in)	28 D (in)	90 D (in)	28 D (in)	90 D (in)
1.55	0.87	1.45	0.74	1.17	0.71
1.60	0.76	1.38	0.70	1.27	0.80
1.62	0.85	1.44	0.61	1.30	0.72

480 - 0.45		530 - 0.45	
28 D (in)	90 D (in)	28 D (in)	90 D (in)
1.19	0.75	1.27	0.70
1.26	0.82	1.30	0.73
1.32	0.81	1.19	0.75

430 - 0.35		480 - 0.35		530 - 0.35	
28 D (mm)	90 D (mm)	28 D (mm)	90 D (mm)	28 D (mm)	90 D (mm)
25.19	11.13	24.15	11.83	23.32	11.88
24.61	10.69	24.48	12.90	24.74	12.29
25.56	11.46	23.07	12.16	25.29	12.58
	11.42		12.33		

430 - 0.40		480 - 0.40		530 - 0.40	
28 D (mm)	90 D (mm)	28 D (mm)	90 D (mm)	28 D (mm)	90 D (mm)
29.63	13.50	20.40	13.87	29.98	15.80
30.27	15.59	20.29	13.54	30.95	15.45
28.94	14.74	21.49	13.19	28.49	17.40

330 - 0.45		380 - 0.45		430 - 0.45	
28 D (mm)	90 D (mm)	28 D (mm)	90 D (mm)	28 D (mm)	90 D (mm)
39.37	22.22	36.88	18.77	29.79	18.03
40.67	19.31	35.05	17.79	32.29	20.32
41.06	21.62	36.61	15.58	33.03	18.31

480 - 0.45		530 - 0.45	
28 D (mm)	90 D (mm)	28 D (mm)	90 D (mm)
30.17	19.15	32.18	17.86
31.94	20.83	32.97	18.59
33.47	20.64	30.25	19.00

1. FA 15% 430-0.35		3. FA 30% 430-0.35		25. FA 45% 430-0.35	
28 D (in)	90 D (in)	28 D (in)	90 D (in)	28 D (in)	90 D (in)
0.97	0.29	0.67	0.25	0.56	0.13
0.93	0.34	0.72	0.24	0.57	0.13
0.94	0.35	0.69	0.36	0.52	0.12

2. FA 15% 430-0.45		4. FA 30% 430-0.45		26. FA 45% 430-0.45	
28 D (in)	90 D (in)	28 D (in)	90 D (in)	28 D (in)	90 D (in)
1.13	0.47	0.98	0.27	0.64	0.24
1.09	0.41	0.87	0.31	0.55	0.21
1.09	0.40	0.90	0.31	0.60	0.24

5. FA 15% 530-0.35		7. FA 30% 530-0.35		27. FA 45% 530-0.35	
28 D (in)	90 D (in)	28 D (in)	90 D (in)	28 D (in)	90 D (in)
0.75	0.31	0.63	0.20	0.42	0.09
0.72	0.29	0.67	0.31	0.51	0.13
0.66	0.31	0.59	0.28	0.52	0.13

6. FA 15% 530-0.45		8. FA 30% 530-0.45		28. FA 45% 530-0.45	
28 D (in)	90 D (in)	28 D (in)	90 D (in)	28 D (in)	90 D (in)
1.18	0.39	0.94	0.31	0.55	0.23
1.17	0.38	0.88	0.29	0.59	0.23
1.15	0.44	0.93	0.35	0.61	0.21

9. S 15% 430-0.35		11. S 30% 430-0.35		21. S 45% 430-0.35	
28 D (in)	90 D (in)	28 D (in)	90 D (in)	28 D (in)	90 D (in)
0.59	0.37	0.39	0.28	0.27	0.20
0.57	0.43	0.39	0.28	0.24	0.22
0.56	0.43	0.37	0.27	0.33	0.21

10. S 15% 430-0.45		12. S 30% 430-0.45		22. S 45% 430-0.45	
28 D (in)	90 D (in)	28 D (in)	90 D (in)	28 D (in)	90 D (in)
0.72	0.51	0.55	0.32	0.31	0.26
0.92	0.55	0.53	0.35	0.35	0.25
0.82	0.55	0.54	0.35	0.36	0.23

13. S 15% 530-0.35		15. S 30% 530-0.35		24. S 45% 530-0.35	
28 D (in)	90 D (in)	28 D (in)	90 D (in)	28 D (in)	90 D (in)
0.51	0.35	0.45	0.27	0.25	0.17
0.48	0.38	0.45	0.30	0.26	0.20
0.49	0.37	0.42	0.29	0.29	0.18

14. S 15% 530-0.45		16. S 30% 530-0.45		23. S 45% 530-0.45	
28 D (in)	90 D (in)	28 D (in)	90 D (in)	28 D (in)	90 D (in)
0.71	0.56	0.56	0.39	0.36	0.17
0.72	0.58	0.59	0.43	0.40	0.22
0.74	0.57	0.61	0.34	0.39	0.20

17. SF 7.5% 430-0.35		18. SF 7.5% 430-0.45		19. SF 7.5% 530-0.35	
28 D (in)	90 D (in)	28 D (in)	90 D (in)	28 D (in)	90 D (in)
0.19	0.13	0.25	0.16	0.18	0.08
0.17	0.09	0.28	0.16	0.16	0.11
0.16	0.13	0.38	0.17	0.19	0.10

20. SF 7.5% 530-0.45	
28 D (in)	90 D (in)
0.37	0.19
0.34	0.20
0.32	0.29

1. FA 15% 430-0.35		3. FA 30% 430-0.35		25. FA 45% 430-0.35	
28 D (mm)	90 D (mm)	28 D (mm)	90 D (mm)	28 D (mm)	90 D (mm)
24.68	7.43	16.98	6.28	14.16	3.34
23.51	8.66	18.40	6.18	14.46	3.22
23.82	9.00	17.55	9.25	13.18	3.06

2. FA 15% 430-0.45		4. FA 30% 430-0.45		26. FA 45% 430-0.45	
28 D (mm)	90 D (mm)	28 D (mm)	90 D (mm)	28 D (mm)	90 D (mm)
28.70	12.03	24.95	6.92	16.31	6.08
27.58	10.43	22.07	7.83	14.05	5.46
27.65	10.15	22.87	7.83	15.30	6.09

5. FA 15% 530-0.35		7. FA 30% 530-0.35		27. FA 45% 530-0.35	
28 D (mm)	90 D (mm)	28 D (mm)	90 D (mm)	28 D (mm)	90 D (mm)
19.12	7.90	15.93	5.02	10.77	2.41
18.23	7.38	16.94	7.79	12.95	3.27
16.73	7.81	15.00	7.19	13.29	3.30

6. FA 15% 530-0.45		8. FA 30% 530-0.45		28. FA 45% 530-0.45	
28 D (mm)	90 D (mm)	28 D (mm)	90 D (mm)	28 D (mm)	90 D (mm)
29.92	9.85	23.98	7.76	14.04	5.73
29.77	9.73	22.34	7.27	14.92	5.81
29.30	11.15	23.62	8.87	15.42	5.23

9. S 15% 430-0.35		11. S 30% 430-0.35		21. S 45% 430-0.35	
28 D (mm)	90 D (mm)	28 D (mm)	90 D (mm)	28 D (mm)	90 D (mm)
14.87	9.28	9.80	7.18	6.82	5.08
14.55	10.91	9.96	7.19	6.21	5.62
14.25	10.95	9.36	6.78	8.37	5.34

10. S 15% 430-0.45		12. S 30% 430-0.45		22. S 45% 430-0.45	
28 D (mm)	90 D (mm)	28 D (mm)	90 D (mm)	28 D (mm)	90 D (mm)
18.33	12.94	13.85	8.00	7.82	6.58
23.33	14.08	13.42	8.81	8.83	6.34
20.78	13.90	13.65	9.01	9.08	5.80

13. S 15% 530-0.35		15. S 30% 530-0.35		24. S 45% 530-0.35	
28 D (mm)	90 D (mm)	28 D (mm)	90 D (mm)	28 D (mm)	90 D (mm)
0.51	0.35	11.41	6.98	6.23	4.41
0.48	0.38	11.32	7.70	6.72	5.14
0.49	0.37	10.65	7.48	7.34	4.49

14. S 15% 530-0.45		16. S 30% 530-0.45		23. S 45% 530-0.45	
28 D (mm)	90 D (mm)	28 D (mm)	90 D (mm)	28 D (in)	90 D (in)
18.05	14.22	14.21	9.94	9.18	4.23
18.36	14.73	14.89	10.92	10.10	5.50
18.88	14.39	15.52	8.65	9.88	5.00

17. SF 7.5% 430-0.35		18. SF 7.5% 430-0.45		19. SF 7.5% 530-0.35	
28 D (mm)	90 D (mm)	28 D (mm)	90 D (mm)	28 D (mm)	90 D (mm)
4.71	3.26	6.37	4.17	4.48	2.11
4.37	2.24	7.20	3.97	4.07	2.78
4.09	3.32	9.58	4.30	4.87	2.62

20. SF 7.5% 530-0.45	
28 D (mm)	90 D (mm)
9.43	4.89
8.62	5.15
8.16	7.40

Appendix C - Surface Resistivity Results

Time of Measurement (Min)	Mix ID	530-0.35 28 Day										
	Sample 1				Sample 2				Sample 3			
	1	2	3	4	1	2	3	4	1	2	3	4
0	11.3	11.6	11.2	11.3	11.6	10.5	11.7	12.3	12.1	12.2	12.1	11.8
10	11	11.4	11.2	11.2	11.5	10.3	11.7	12	12.1	12.2	12.1	11.6
30	10.8	11.1	10.8	11	11.3	10.3	11.7	11.8	11.7	11.8	11.9	11.2
40	10.5	11.1	10.6	10.7	11	10.1	11.6	11.6	11.4	11.7	11.7	11.1
60	10.4	10.6	10.5	10.6	10.6	9.7	10.6	11.2	11.1	11	11.2	10.8

Time of Measurement (Min)	Mix ID	480-0.35 28 Day										
	Sample 1				Sample 2				Sample 3			
	1	2	3	4	1	2	3	4	1	2	3	4
0	11.3	12.3	12.2	11.8	11.5	11.8	11.9	11.3	12.6	12.3	12.4	13.6
5	11.7	12.2	12	11.7	11.3	11.4	11.9	11.2	12.6	12.3	12.3	13.4
10	11.5	11.9	11.9	11.6	11.3	11.4	11.8	11.1	12.5	12.2	12.2	13.3
20	11.4	11.9	11.8	11.6	11.2	11.3	11.7	11	12.4	12.1	12.1	13.1
30	11.2	11.8	11.5	11.4	11	11.1	11.5	10.8	12.2	11.9	12	12.8
40	11.1	11.6	11.4	11.3	11	10.9	11.4	10.7	12	11.8	12	12.7
60	10.8	11.4	11.2	11.1	10.6	10.7	11.3	10.5	11.8	11.8	11.6	12.3

Time of Measurement (Min)	Mix ID	430-0.35 28 Day										
	Sample 1				Sample 2				Sample 3			
	1	2	3	4	1	2	3	4	1	2	3	4
0	13	13.9	14.2	13.3	13.4	12.7	12.4	13.1	12.9	14	13.5	12.6
5	12.9	13.9	14.1	13.2	13.3	12.8	12.3	12.9	12.8	13.9	13.5	12.4
10	12.9	13.8	14.1	13	13.3	12.7	12.3	12.7	12.7	13.7	13.4	12.4
20	12.7	13.7	14	12.8	13.1	12.5	12.4	12.6	12.5	13.6	13.3	12.4
30	12.6	13.4	13.8	12.6	12.9	12.5	12.3	12.3	12.4	13.4	13	12.3
40	12.5	13.2	13.9	12.4	12.7	12.2	12.3	12.2	12.4	13.2	12.9	12.1
60	12.3	12.8	13.5	12.1	12.5	12	12.2	12	12.2	12.9	12.6	11.9

Time of Measurement (Min)	Mix ID	530-0.4 28 Day										
	Sample 1				Sample 2				Sample 3			
	1	2	3	4	1	2	3	4	1	2	3	4
0	7.8	7.7	7.7	7.6	8.2	7	7.3	8	7.2	7.8	7.4	7.5
5	7.7	7.7	7.5	7.6	8.2	7	7.3	8	7.2	7.8	7.3	7.4
10	7.7	7.7	7.4	7.6	7.9	7	7.2	7.9	7.1	7.7	7.2	7.4
20	7.6	7.7	7.4	7.5	7.8	7	7	7.9	7	7.6	7.2	7.4
30	7.5	7.5	7.3	7.5	7.7	6.9	6.9	7.8	7	7.5	7.1	7.2
40	7.5	7.5	7.3	7.4	7.7	6.7	6.8	7.8	7	7.5	7	7.1
60	7.3	7.4	7.3	7.3	7.6	6.7	6.7	7.7	6.7	7.3	6.8	7

Time of Measurement (Min)	Mix ID	480-0.4 28 Day										
	Sample 1				Sample 2				Sample 3			
	1	2	3	4	1	2	3	4	1	2	3	4
0	8.6	8.2	7.9	8.4	8.6	8.4	8.7	8.3	8.5	8.4	7.8	8
5	8.6	8.2	8	8.3	8.6	8.4	8.8	8.3	8.4	8.3	7.7	8
10	8.5	8	7.9	8.3	8.6	8.3	8.7	8.2	8.3	8.3	7.7	7.9
20	8.4	7.9	7.7	8.1	8.4	8.2	8.6	8.1	8.2	8.3	7.6	7.8
30	8.3	7.8	7.6	8.1	8.3	8	8.4	8	8	8.2	7.5	7.8
40	8.2	7.7	7.5	8	8.3	7.9	8.3	7.8	8	8.1	7.4	7.7
60	8.1	7.6	7.4	7.8	8.1	7.8	8.1	7.7	7.9	7.9	7.3	7.5

Time of Measurement (Min)	Mix ID	430-0.4 28 Day										
	Sample 1				Sample 2				Sample 3			
	1	2	3	4	1	2	3	4	1	2	3	4
0	10.1	9.4	10	8.8	9.5	9.8	11	8.8	9.6	8.7	9.4	9.4
5	10.1	9.4	9.9	8.8	9.5	9.7	10.9	8.8	9.5	8.7	9.3	9.4
10	10	9.3	9.8	8.7	9.5	9.6	10.8	8.8	9.5	8.6	9.3	9.3
20	9.9	9.1	9.8	8.6	9.4	9.6	10.8	8.7	9.3	8.5	9.2	9.1
30	9.8	9	9.7	8.5	9.2	9.5	10.7	8.5	9.1	8.3	9.1	9.1
40	9.6	8.9	9.5	8.4	9.1	9.3	10.4	8.4	9.1	8.2	9	9
60	9.4	8.7	9.4	8.2	8.9	9.1	10.3	8.2	8.9	8.1	8.8	8.7

Time of Measurement (Min)	Mix ID	380-0.4 28 Day										
	Sample 1				Sample 2				Sample 3			
	1	2	3	4	1	2	3	4	1	2	3	4
0	13.5	12.6	11.6	11.6	11.9	11.9	12.5	12.7	12.1	12.7	12.2	11.7
5	13.5	12.5	11.5	11.4	11.8	11.9	12.3	12.6	12	12.5	12.2	11.6
10	13.5	12.3	11.5	11.3	11.6	11.8	12.3	12.6	12	12.5	12.2	11.5
20	13.3	12.2	11.3	11.3	11.4	11.6	12.1	12.3	11.8	12.3	12.1	11.4
30	13.2	12	11.2	11.1	11.3	11.4	12	12.2	11.7	12.3	11.9	11.2
40	13	11.8	11.1	11	11	11.4	11.9	12	11.5	12.1	11.8	11.1
60	12.8	11.7	10.9	10.7	10.9	11	11.8	11.8	11.3	11.9	11.6	10.9

Time of Measurement (Min)	Mix ID	530-0.45 28 Day										
	Sample 1				Sample 2				Sample 3			
	1	2	3	4	1	2	3	4	1	2	3	4
0	6.1	5.6	7	6.5	7	6.2	5.9	6.6	7	6.3	6.2	6.7
5	6.1	5.6	6.9	6.5	7	6.2	5.9	6.6	7	6.3	6.2	6.7
10	6.1	5.6	6.8	6.4	7	6.1	5.8	6.5	6.8	6.3	6.2	6.6
20	6	5.4	6.7	6.3	6.9	6.1	5.7	6.4	6.7	6.2	6.1	6.5
30	5.9	5.3	6.7	6.2	6.9	6.1	5.7	6.3	6.6	6.1	6.1	6.4
40	5.8	5.3	6.6	6.2	6.8	6	5.6	6.3	6.5	6	6	6.4
60	5.7	5.2	6.5	6	6.7	5.9	5.6	6.3	6.5	5.9	5.9	6.4

Time of Measurement (Min)	Mix ID	480-0.45 28 Day										
	Sample 1				Sample 2				Sample 3			
	1	2	3	4	1	2	3	4	1	2	3	4
0	6.8	7.7	8.3	6.7	7.2	7.1	7.3	7.9	6.9	7.5	7.7	7.5
5	6.8	7.7	8.3	6.7	7.2	7.1	7.3	7.8	6.9	7.4	7.7	7.5
10	6.7	7.6	8.2	6.6	7.2	7.1	7.2	7.8	6.8	7.4	7.5	7.4
20	6.6	7.6	8.1	6.6	7.1	7.1	7.1	7.8	6.8	7.3	7.5	7.4
30	6.6	7.5	8	6.5	7	7	7	7.6	6.7	7.2	7.3	7.3
40	6.5	7.4	8	6.4	6.8	6.8	6.9	7.6	6.6	7.1	7.2	7.2
60	6.4	7.2	7.8	6.3	6.7	6.8	6.8	7.5	6.5	7	7.1	7

Time of Measurement (Min)	Mix ID	430-0.45 28 Day										
	Sample 1				Sample 2				Sample 3			
	1	2	3	4	1	2	3	4	1	2	3	4
0	7.8	7.8	8.2	8.4	8.6	8.8	8.2	8.3	8.3	8.6	8.4	8.1
5	7.8	7.8	8.2	8.3	8.6	8.8	8.2	8.3	8.3	8.6	8.4	8.1
10	7.7	7.8	8.1	8.2	8.5	8.7	8.1	8.2	8.2	8.6	8.3	8
20	7.7	7.7	8	8.2	8.5	8.7	8	8.2	8.1	8.5	8.3	8
30	7.5	7.6	7.8	8.1	8.4	8.7	8	8.1	8	8.4	8.2	7.9
40	7.5	7.6	7.7	8	8.4	8.6	7.8	8.1	7.9	8.3	8	7.8
60	7.4	7.4	7.7	7.9	8.2	8.4	7.8	8	7.9	8.2	7.9	7.7

Time of Measurement (Min)	Mix ID	380-0.45 28 Day										
	Sample 1				Sample 2				Sample 3			
	1	2	3	4	1	2	3	4	1	2	3	4
0	8.5	8.4	9.3	8.6	8.5	9.2	9	9	8.9	8.3	9	8.6
5	8.5	8.4	9.3	8.6	8.5	9.1	8.9	9	8.9	8.3	9	8.6
10	8.4	8.3	9.3	8.6	8.4	9.1	8.9	8.9	8.7	8.2	8.9	8.5
20	8.4	8.3	9.2	8.6	8.4	9	8.8	8.9	8.7	8.2	8.9	8.3
30	8.3	8.2	9.1	8.6	8.3	9	8.7	8.7	8.7	8.1	8.8	8.2
40	8.2	8.1	9	8.5	8.2	9	8.7	8.7	8.6	7.9	8.7	8.2
60	8.1	8.1	9	8.4	8	8.8	8.6	8.5	8.5	7.8	8.6	8

Time of Measurement (Min)	Mix ID	330-0.45 28 Day										
	Sample 1				Sample 2				Sample 3			
	1	2	3	4	1	2	3	4	1	2	3	4
0	9	10	9.5	8.7	8.8	9	9.7	9.5	9.9	10.4	10.2	9.9
5	8.9	9.9	9.5	8.7	8.8	9	9.7	9.4	9.9	10.4	10.1	9.9
10	8.9	9.9	9.5	8.7	8.8	9	9.6	9.4	9.8	10.3	10	9.8
20	8.9	9.8	9.4	8.5	8.7	9	9.6	9.3	9.7	10.2	9.8	9.8
30	8.9	9.8	9.4	8.4	8.7	8.8	9.6	9.3	9.6	10.1	9.8	9.8
40	8.8	9.8	9.3	8.3	8.6	8.8	9.5	9.3	9.6	9.9	9.8	9.7
60	8.7	9.7	9.2	8.2	8.5	8.6	9.4	9.2	9.4	9.7	9.6	9.6

Time of Measurement (min)	Mix ID	530-0.35 90 Day						
	Sample 1				Sample 2			
	1	2	3	4	1	2	3	4
0	23.7	25.4	26	23.5	25.4	24.1	23	25.2
10	23.1	24.4	26.1	22.4	25.3	23.7	21.5	24.8
20	22.2	24	25.2	21.8	24.7	23.1	20.8	24.8
30	21.9	23.4	24.8	21.5	24.3	22.4	20.9	24.3
40	21.7	23	24.6	21.3	23.8	22.2	20.7	23.8
60	21.1	23.3	23.7	20.5	23.3	21.6	20.3	23
Time of Measurement (min)	Sample 3				Sample 4			
	1	2	3	4	1	2	3	4
0	24.7	23.6	23.3	23.7	23.3	23.2	22.6	22.7
10	24.9	23.8	23.2	21.8	22.8	23	21.9	21.8
20	24.3	23	23.1	21.6	22.6	22.2	21.7	21.3
30	23.5	22.6	22.2	21.3	21.7	21.6	20.9	20.9
40	23.3	22.2	22.4	20.6	21.5	21	20.3	20.5
60	23	21.7	21.1	20.2	21	20.2	19.8	20

Time of Measurement (min)	Mix ID	480-0.35 90 Day						
	Sample 1				Sample 2			
	1	2	3	4	1	2	3	4
0	29.2	29.6	27.9	27.8	30.1	30.4	27.8	29.2
10	28.7	29.3	27.1	26.7	29.1	29.9	27.5	29.1
20	27.9	28.7	26.2	26.3	28.4	29.2	27.3	28.3
30	27.5	28	26.3	25.7	27.7	28.4	26.9	27.7
40	27	27.6	25.3	25.6	27	27.9	26.4	27.6
60	25.8	26.6	24.9	24.1	26.4	26.9	26.1	26.9
Time of Measurement (min)	Sample 3				Sample 4			
	1	2	3	4	1	2	3	4
0	28.6	27.6	30.4	29.3	31.5	27.5	27.1	29.1
10	27.7	27	29.5	29	30.9	27.2	26.7	28.1
20	27.5	26.7	29.4	28.4	30.4	26.5	25.8	27.3
30	26.2	26	28.7	27.8	29.7	26.4	25.7	27.2
40	25.6	25.4	28.6	27.1	29.3	25.8	24.9	26.4
60	25.4	24.7	27.5	26.5	28.1	24.7	24.4	25.6

Time of Measurement (min)	Mix ID	430-0.35 90 Day						
	Sample 1				Sample 2			
	1	2	3	4	1	2	3	4
0	32.9	33.3	36.5	35.3	33.4	31.3	33.5	32.3
10	32.3	32.9	36.2	34.3	33.1	32.4	32.6	31.5
20	32.4	32.4	35.8	33.8	31.9	30.7	31.7	31.2
30	31.5	31.5	35.4	33.6	31.8	30	31.8	30.8
40	31.4	31.3	34.8	33.4	31.1	29.5	31.5	30
60	30.8	30	33.2	31.7	30.1	29	30.1	29.3
Time of Measurement (min)	Sample 3				Sample 4			
	1	2	3	4	1	2	3	4
0	32.4	32.7	33	29.9	32.4	31.9	30.8	35.8
10	32	33.5	32.9	29.8	31.5	31.5	30.6	33.5
20	31.7	32.8	31.6	29.1	30.7	30.8	29.9	32.7
30	31.2	32	31.2	28.6	30.3	29.7	29.2	31.5
40	30.1	30.8	30	28.2	29.4	29.6	29	30.1
60	29.5	30.6	30	27.8	28.8	29.1	28.6	30

Time of Measurement (min)	Mix ID	530-0.4 90 Day						
	Sample 1				Sample 2			
	1	2	3	4	1	2	3	4
0	14	14	13.2	12.4	14.9	14.3	14.2	13.4
10	14	14.3	13.6	12.4	14.7	14.7	14.2	13.3
20	13.9	14.3	13.6	12.4	14.6	14.7	14.2	13.6
30	14.1	14.5	13.6	12.4	14.6	14.8	14.3	13.7
40	14.3	14.3	13.4	12.6	14.9	14.8	14.3	13.7
60	14.3	14.3	13.5	12.7	14.8	14.9	14.2	13.9
Time of Measurement (min)	Sample 3				Sample 4			
	1	2	3	4	1	2	3	4
0	13.3	13.1	11.9	13.2	13.7	12.7	13.1	11.7
10	13.2	12.9	11.9	13.1	13.6	12.8	13.1	11.7
20	13.1	13	11.9	13.3	13.6	13.1	13.1	11.6
30	13.2	13	12	13.4	13.5	13	13.1	11.6
40	13	13.1	12.2	13.6	13.7	13.1	13.3	11.7
60	13.2	13	12.1	13.2	13.8	12.9	13.2	11.7

Time of Measurement (min)	Mix ID	480-0.4 90 Day						
	Sample 1				Sample 2			
	1	2	3	4	1	2	3	4
0	24.2	27	27.2	25	24.8	25.8	26.3	24
10	23.6	26.6	26.5	24.1	24.3	25.3	25.7	23.3
20	23.3	25.7	26.4	24	23.9	24.7	25.1	22.9
30	23.1	25.1	25.6	23.4	23.5	24.3	24.9	22.4
40	22.9	25.1	25.3	23	23.1	23.8	24.5	22
60	21.4	24.6	24.6	22.4	22.6	23.1	24.1	21.7
Time of Measurement (min)	Sample 3				Sample 4			
	1	2	3	4	1	2	3	4
0	24.2	24.7	26.5	26.4	24.1	24.8	27.1	25.9
10	23.5	24	26.2	26.4	23.7	24.7	26.5	25.1
20	232	23.7	25.5	25.7	23.3	24.2	26.3	24.8
30	22.8	23.5	25.4	25.8	23.1	23.7	25.4	24.3
40	22.7	22.9	24.7	25.7	22.9	23.5	24.9	24.1
60	22.1	22.4	24.1	24.7	22.4	22.9	24.6	23.4

Time of Measurement (min)	Mix ID	430-0.4 90 Day						
	Sample 1				Sample 2			
	1	2	3	4	1	2	3	4
0	21.2	18.8	18.9	18.5	18.5	16.4	17.8	18.2
10	21	18.5	19.1	18.5	18.4	16.3	17.9	17.9
20	20.4	18.5	19	18.6	18.4	16.2	17.3	17.7
30	20.4	18.3	18.2	18.5	18.4	16.2	17.5	17.5
40	20	18.3	18.7	18.7	18.3	16.1	17.1	17.4
60	20.3	17.8	18.7	18.3	18.1	15.8	17.1	17.4
Time of Measurement (min)	Sample 3				Sample 4			
	1	2	3	4	1	2	3	4
0	18.3	18.8	17.1	18.2	19.2	19.6	19.2	17.6
10	18.1	18.8	17.3	17.9	16.9	19.5	19.2	17.5
20	18	18.7	16.9	18.1	16.7	19.3	18.9	17.4
30	17.8	18.4	17.2	18.1	16.6	19.3	19.2	17.2
40	17.6	18.7	17	18	16.6	19.3	19.2	17.4
60	17.6	18.2	16.7	17.5	16.5	19.2	19.1	17.4

Time of Measurement (min)	Mix ID	380-0.4 90 Day						
	Sample 1				Sample 2			
	1	2	3	4	1	2	3	4
0	22.7	21.3	22.7	22.9	22.7	21.9	24.1	21.5
10	22.3	21.2	22.4	22.5	22.5	21.7	24.1	21.1
20	21.9	20.8	21.7	21.9	22	21.3	23.6	20.8
30	21.7	20.3	21.6	21.6	21.7	21	22.9	20.6
40	21.3	20.3	21.5	21.2	21.3	20.7	22.6	20
60	20.8	19.7	20.3	20.7	20.7	20.3	22	19.7
Time of Measurement (min)	Sample 3				Sample 4			
	1	2	3	4	1	2	3	4
0	21.6	21.2	21.6	19.2	22.8	21.6	22.9	24.7
10	21.4	20.7	21.3	18.8	22.7	21.3	22.7	24.6
20	21.1	20.6	20.9	18.6	22.2	20.8	22.1	24.4
30	20.6	20.1	20.3	18.3	21.8	20.7	21.7	23.8
40	20.2	19.9	20.3	18	21.6	20.1	21.4	23.4
60	20	19.4	19.7	17.6	21	19.9	20.7	22.9

Time of Measurement (min)	Mix ID	530-0.45 90 Day						
	Sample 1				Sample 2			
	1	2	3	4	1	2	3	4
0	12.2	12.7	11.8	11.5	10.9	12.1	13.3	12.2
10	12	12.5	11.6	11.4	10.7	12	13	11.8
20	11.7	12.3	11.3	11.1	10.6	11.6	12.8	11.7
30	11.6	12	11.1	10.9	10.4	11.2	12.6	11.5
40	11.4	11.7	11	10.7	10.2	11	12.3	11.3
60	11	11.6	10.6	10.6	10	10.8	12.1	11
Time of Measurement (min)	Sample 3				Sample 4			
	1	2	3	4	1	2	3	4
0	13	11.6	12.9	13	10.7	11.7	11.8	10.8
10	12.8	11.4	12.6	12.6	10.6	11.6	11.4	10.6
20	12.6	11.3	12.3	12.6	10.4	11.3	11.3	10.5
30	12.4	10.9	12.1	12.3	10.2	11.2	11	10.3
40	12.2	10.8	11.9	12.2	10.1	11	10.8	10.1
60	12	10.5	11.6	12	9.7	10.5	10.6	9.8

Time of Measurement (min)	Mix ID	480-0.45 90 Day						
	Sample 1				Sample 2			
	1	2	3	4	1	2	3	4
0	11.7	13.2	11.4	11.2	12.6	13	12.3	13.9
10	11.5	13.1	11.1	11	12.4	12.9	12.3	13.9
20	11.3	12.7	10.7	11	12.3	12.8	12.1	13.5
30	11.2	12.6	10.7	10.6	12.1	12.7	12	13.5
40	11	12.4	10.4	10.4	11.9	12.6	11.8	13.3
60	10.8	12	10.2	10.2	11.8	12.1	11.7	13.2
Time of Measurement (min)	Sample 3				Sample 4			
	1	2	3	4	1	2	3	4
0	11.2	11.8	11.9	12.2	13	12.2	13	12.8
10	10.9	11.5	11.8	12	12.9	12.1	13	12.5
20	10.7	11.5	11.5	12	12.7	11.9	12.7	12.4
30	10.5	11.2	11.3	11.7	15.5	11.7	12.7	12.3
40	10.3	11.2	11.3	11.5	12.2	11.6	12.2	12.1
60	10.2	10.9	10.8	11.3	12	11.4	12	11.7

Time of Measurement (min)	Mix ID	430-0.45 90 Day						
	Sample 1				Sample 2			
	1	2	3	4	1	2	3	4
0	14.4	14.7	15.7	15.5	17.4	15.9	17.7	16.9
10	14.3	14.4	15.5	15.2	17.4	15.6	17.2	16.7
20	14.1	14.3	15.2	14.9	17.1	15.4	17	16.1
30	13.8	13.8	15	14.7	16.6	15.1	16.8	15.9
40	13.7	13.6	14.6	14.4	16.4	14.8	16.4	15.7
60	13.1	13.2	14.1	13.9	15.9	14.3	15.8	15.2
Time of Measurement (min)	Sample 3				Sample 4			
	1	2	3	4	1	2	3	4
0	16.2	15.6	14.8	14.8	15.4	15.6	15.4	14.3
10	16.1	15.4	14.6	14.7	15.3	15	15.1	14.2
20	15.7	15.1	14.2	14.5	15.1	14.7	14.7	13.9
30	15.4	14.9	14	14.1	14.9	14.5	14.7	13.7
40	15.3	14.7	13.7	13.6	14.6	14.2	14.5	13.5
60	14.8	14.3	13.4	13.5	14.3	13.6	14.2	13

Time of Measurement (min)	Mix ID	380-0.4 90 Day						
	Sample 1				Sample 2			
	1	2	3	4	1	2	3	4
0	20.9	19.9	19.7	19.9	19.4	19.1	20.9	22.3
10	20.9	19.2	19.6	19.9	19.4	19	20.7	22
20	20.5	19.2	19.1	19.7	19.3	18.7	20.5	21.3
30	20.2	18.4	18.5	19.2	19.1	18.4	20.1	21
40	20	18.2	18	18.9	18.6	18.2	19.7	20.7
60	19.4	17.8	17.2	18.6	18	17.7	19.3	20.2
Time of Measurement (min)	Sample 3				Sample 4			
	1	2	3	4	1	2	3	4
0	20.1	20.1	18.4	19	21.2	23.8	21.6	20.9
10	19.8	19.9	18	18.6	20.8	23	21.2	20.7
20	19.2	19.6	17.7	18.3	20.6	22.7	20.9	20.5
30	19.2	19.2	17.5	18	20.2	22.5	20.6	20.1
40	18.8	18.7	17.4	17.7	20	22.3	20.5	20
60	18.6	18.3	16.9	17.2	19.5	21.6	20	19.5

Time of Measurement (min)	Mix ID	330-0.45 90 Day						
	Sample 1				Sample 2			
	1	2	3	4	1	2	3	4
0	23.5	24.7	22.8	22.3	20.9	20.2	21.7	22.8
10	23.1	24.4	22	21.7	20.9	20.1	20.5	22.1
20	23	24.1	21.6	21.5	20.2	19.8	19.9	21.6
30	22.5	23.8	21.3	21.1	20	19.6	19.8	21.6
40	22.2	23.3	20.9	21	19.7	19.4	19.5	21.3
60	21.6	23.2	20.6	20.5	19.5	19.1	19	20.8
Time of Measurement (min)	Sample 3				Sample 4			
	1	2	3	4	1	2	3	4
0	22.4	21.6	21.7	23.7	24.2	22.1	22.3	25.1
10	22.2	21.3	21.3	23.7	24	21.7	22	25.1
20	22.1	20.6	21	23.5	23.7	21.3	21.9	24.7
30	21.7	20.3	20.8	23.2	23.1	20.9	21.3	24.4
40	21.6	20	20.6	23	22.7	20.6	21.3	23.8
60	20.9	19.6	20.3	22.5	22.5	20.3	20.9	23.3

Time of Measurement (min)	Mix ID	FA 15% 430-0.35 28 Day						
	Sample 1				Sample 2			
	1	2	3	4	1	2	3	4
0	14.3	12.9	12.2	14	13	14.1	13.5	13.6
10	14.4	12.6	12.1	13.9	12.7	13.9	13.5	13.6
20	14.4	12.6	11.9	13.9	12.7	13.8	13.3	13.5
30	14.2	12.4	11.9	13.9	12.7	13.7	13	13.5
40	14.1	12.2	11.8	13.6	12.7	13.7	13	13.5
60	13.9	12.1	11.5	13.6	12.6	13.6	12.9	13.2
Time of Measurement (min)	Sample 3				Sample 4			
	1	2	3	4	1	2	3	4
0	14.7	12.7	13.2	13.3	14	14.2	14.9	14.3
10	14.3	12.7	13.7	13	13.7	14	14.4	14.2
20	14	12.6	13.7	12.9	13.6	13.8	14.7	14
30	14.3	12.3	13.5	12.8	13.6	13.7	14.5	13.7
40	14.3	12.3	13.5	12.6	13.4	13.7	14.3	14
60	13.9	12	13.4	12.7	13.2	13.3	14.3	13.9

Time of Measurement (Min)	Mix ID	FA 15% 430-0.45 28 Day										
	Sample 1				Sample 2				Sample 3			
	1	2	3	4	1	2	3	4	1	2	3	4
0	11	10.5	10.4	10.9	9.8	9.5	9.8	10.4	9.9	10	9.4	9.9
10	10.6	10.5	10.2	10.7	9.5	9.5	9.6	10.5	10.2	9.9	9.4	9.6
20	10.6	10.4	10	10.7	9.5	9.5	9.8	10.4	10.1	9.9	9.3	9.6
30	10.3	10.4	9.8	10.6	9.4	9.4	9.8	10.4	10	9.9	9.2	9.6
40	10.3	10.3	9.8	10.6	9.3	9.3	9.7	10.3	9.9	9.8	9.2	9.6
60	10.2	10.1	9.6	10.4	9.2	9.2	9.7	10.2	9.9	9.8	9.2	9.5

Time of Measurement (Min)	Mix ID	FA 30% 430-0.35 28 Day										
	Sample 1				Sample 2				Sample 3			
	1	2	3	4	1	2	3	4	1	2	3	4
0	22.1	21.3	24	24	22.2	22.5	21.8	22.7	24.3	22.9	21.6	24.4
10	22.6	20.8	24	24	21.5	22.4	22	22.8	24.2	22.9	21.4	24.1
20	21.3	20.8	23.5	23.3	21	22.1	21.8	22.6	23.1	22.6	21	24.1
30	22.2	20.5	23.5	23.1	20.9	22.1	21.4	21.4	23	21.8	21	23.9
40	21.5	20.6	23.5	22.9	20.7	22.1	21.3	22.4	22.9	21.9	20.9	24
60	21.8	20.4	23.3	22.7	20.5	21.8	21.2	22.2	22.5	21.7	20.9	23.8

Time of Measurement (Min)	Mix ID	FA 30% 430-0.45 28 Day										
	Sample 1				Sample 2				Sample 3			
	1	2	3	4	1	2	3	4	1	2	3	4
0	13.8	15.1	14.2	14	15.1	14.1	14.7	14.4	14	14.3	15.7	15.6
10	13.3	15	14	13.9	15	14	14.6	14.3	13.7	13.9	15.6	15.6
20	13.3	14.9	14	13.7	14.9	14	14.6	14.2	13.8	13.9	15.5	15.4
30	13.2	14.8	14.1	13.7	14.9	13.9	14.5	14	13.9	13.9	15.5	15.5
40	13.3	14.8	14	13.5	14.7	13.9	14.3	14	13.6	13.7	15.4	15.5
60	12.9	14.5	14	13.4	14.5	13.8	14.3	13.8	13.5	13.6	15.2	15.3

Time of Measurement (Min)	Mix ID	FA 15% 530-0.35 28 Day										
	Sample 1				Sample 2				Sample 3			
	1	2	3	4	1	2	3	4	1	2	3	4
0	15.5	16.7	15.1	16.2	18.5	16.9	17.4	17.9	15.4	15	16.2	17
10	15.3	16.5	15	16	18	16.6	17.1	17.6	15.3	14.8	15.9	17.1
20	15.2	16.4	15	15.9	17.7	16.5	17	17.4	15.1	14.7	16.1	16.9
30	14.8	16.2	14.8	15.6	17.2	16.4	16.8	17	14.9	14.5	16	17
40	14.8	15.9	14.5	15.3	17.1	16.2	16.7	17	14.9	14.5	16.1	16.8
60	14.7	15.8	14.1	15.3	16.8	15.9	16.5	16.9	14.5	14.5	15.6	16.6

Time of Measurement (Min)	Mix ID	FA 15% 530-0.45 28 Day										
	Sample 1				Sample 2				Sample 3			
	1	2	3	4	1	2	3	4	1	2	3	4
0	8	7.6	7.4	8	8.5	8.3	9.4	8.7	8.5	8.3	8.7	7.8
10	8	7.4	7.4	7.8	8.4	8.3	9.4	8.5	8.5	8.3	8.6	7.7
20	7.9	7.2	7.4	7.8	8.4	8.3	9.3	8.5	8.5	8.2	8.5	7.6
30	7.9	7.3	7.3	7.8	8.4	8.2	9.3	8.5	8.4	8.2	8.5	7.6
40	7.8	7.3	7.3	7.7	8.4	8.2	9.2	8.4	8.4	8.2	8.5	7.6
60	7.7	7.1	7.1	7.5	8.4	8.2	9	8.3	8.4	8	8.5	7.6

Time of Measurement (Min)	Mix ID	FA 30% 530-0.35 28 Day										
	Sample 1				Sample 2				Sample 3			
	1	2	3	4	1	2	3	4	1	2	3	4
0	18.6	21	19	19.1	20.7	19.9	19.6	18	19.2	19.3	18.2	19
10	18.5	20.9	19	19.1	20.7	19.8	19.3	18	19.1	19	18.2	18.9
20	18.5	19.9	18.9	18.8	20.7	19.8	19.6	17.9	18.9	18.8	18.1	18.8
30	18.3	20	18.6	18.8	20.6	19.6	19.6	17.6	18.9	18.6	17.9	18.8
40	18.1	19.6	18.1	18.5	20.2	19.2	19.3	17.4	18.7	18.5	17.9	18.7
60	18.1	19.5	17.8	18.4	20.2	19.2	18.9	17.2	18.3	18.2	17.4	18.3

Time of Measurement (Min)	Mix ID	FA 30% 530-0.45 28 Day										
	1				2				3			
	1	2	3	4	1	2	3	4	1	2	3	4
0	11.2	10.7	11.9	12.7	11	12.1	11	11.5	10.4	12.3	11.3	11.3
10	11.1	10.6	11.9	12.5	11	12	11.2	11.5	10.3	12.2	11.1	11.3
20	11	10.6	11.7	12.4	10.9	11.9	11.1	11.3	10.3	12.1	11	11.3
30	11	10.5	11.6	12.2	10.8	11.9	11	11.1	10.3	12.1	11	11.1
40	11	10.4	11.6	12	10.6	11.9	10.9	11	10.2	12	11	11.1
60	11	10.3	11.6	11.9	10.6	11.8	10.7	10.9	10.1	11.9	11	11.1

Time of Measurement (Min)	Mix ID	S 15% 430-0.35 28 Day										
	Sample 1				Sample 2				Sample 3			
	1	2	3	4	1	2	3	4	1	2	3	4
0	26.2	25.1	26.4	24.3	24.1	27.8	24.3	23.8	25.4	25.5	26	26.9
10	26	24.8	26.5	24.2	23.8	27.7	24.2	23.7	25.3	25.2	26	26.6
20	25.7	24.9	26.2	23.9	23.4	27.5	23.9	23.5	25	25.2	25.6	26.6
30	25.9	24.9	26.1	23.8	23.4	27.4	24	23.4	24.7	25	25.5	26.4
40	25.8	24.9	26	23.7	23.4	27.2	23.8	23.4	24.6	24.8	25.3	26.3
60	25	24.2	25.4	23.4	22.7	26.8	26.8	22.6	24.4	24.2	25.2	25.9

Time of Measurement (Min)	Mix ID	S 15% 430-0.45 28 Day										
	Sample 1				Sample 2				Sample 3			
	1	2	3	4	1	2	3	4	1	2	3	4
0	12	12.2	13.2	12.9	13.3	13.7	11.5	13.1	12.8	12.8	13.2	13
10	12.1	12.2	13.3	12.9	12.2	13.5	12	13	12.8	12.8	12.8	13
20	12.1	12.2	13.1	12.8	13.2	13.4	11.9	12.9	12.6	12.8	12.8	12.9
30	12	12.3	12.9	12.7	12.9	13.3	11.7	12.8	12.4	12.8	12.7	12.9
40	12	11.7	12.7	12.5	12.9	13.1	11.7	12.7	12.2	12.4	12.6	12.9
60	12	11.7	12.7	12.5	12.8	13.1	11.5	12.7	12.1	12.3	12.2	12.4

Time of Measurement (Min)	Mix ID	S 30% 430-0.35 28 Day										
	Sample 1				Sample 2				Sample 3			
	1	2	3	4	1	2	3	4	1	2	3	4
0	36.3	38.3	37	35.7	37.7	37.6	37.8	37.2	36	34.2	33.9	35
10	35.5	38	36.8	35.4	37.4	37	36.7	36.1	35.4	33.6	33.9	34.7
20	35.4	37.5	36.3	34.6	37	36.6	36.6	35.3	35.2	33.6	33.4	34
30	34.6	36.5	35.8	34.1	36.7	36	35.8	34.8	34.7	33.6	32.7	34.1
40	34.3	36.2	35.6	33.6	36.5	35.5	35.2	34.3	34.5	33.1	32.5	33.6
60	33.7	35.4	34.6	33.6	35.7	34.4	34.7	33.8	33.6	32.7	31.9	33.1

Time of Measurement (Min)	Mix ID	S 30% 430-0.45 28 Day										
	Sample 1				Sample 2				Sample 3			
	1	2	3	4	1	2	3	4	1	2	3	4
0	26.3	22.4	21.7	22	22.1	22.4	20.2	20.9	20.2	22.4	22.1	21.1
10	24.7	22.3	21.6	21.3	22	21.8	20.5	21.3	19.5	21.7	22.3	21.8
20	25.6	22.1	21.3	21.1	21.7	21.7	20.7	21.2	20.3	21.7	22.1	22
30	25.9	22.5	20.8	21.3	21.2	21.8	19.9	20.8	19.4	21.6	21.9	22.3
40	25.3	22.5	21	20.5	20.7	22	20.1	20.7	20	22	21.9	22.9
60	25.2	21.8	20.9	20.3	21.3	21.3	19.9	20.1	20.4	21.6	21.8	22.5

Time of Measurement (Min)	Mix ID	S 15% 530-0.35 28 Day										
	Sample 1				Sample 2				Sample 3			
	1	2	3	4	1	2	3	4	1	2	3	4
0	20	19.6	19.6	22.3	19.7	19	20	22.1	19.7	20	19.1	20.4
10	20.2	19.1	19.6	22.1	20.1	19	21.3	22.3	20	19.5	19.8	19.8
20	20	19.4	19.6	22.3	19.9	19.1	20.6	21.9	19.8	19.2	19.4	19.6
30	19.8	19.7	18.7	21.8	20.1	17.7	19.7	20.9	19.6	20.4	17.7	18.7
40	19.1	19.2	18.8	22.1	19.2	18.8	20.3	20.2	18	18	18.1	18.6
60	20	19.6	19.8	21.2	19.3	18.7	21.7	21.1	19.8	19.3	19.5	20

Time of Measurement (Min)	Mix ID	S 15% 530-0.45 28 Day										
	Sample 1				Sample 2				Sample 3			
	1	2	3	4	1	2	3	4	1	2	3	4
0	10.5	10.3	10.9	10.6	10.4	10.3	10.8	9.8	10.6	11.5	10	10
10	10.4	10.2	11	11.6	10.5	10.5	11.2	10	10.6	11.5	9.7	10.5
20	10.4	10.3	10.9	12.2	10.9	10.6	11.4	10.1	10.8	11.6	9.8	10.2
30	10.4	10.2	10.8	11.6	10.6	10.6	11.1	10.3	10.5	11.5	10.1	10.1
40	10.2	10	10.6	11.6	10.6	10.6	11.4	10.2	10.6	11.7	9.9	10
60	10.2	10	10.5	11.4	10.8	10.2	11	10	10.4	11.3	9.5	9.8

Time of Measurement (Min)	Mix ID	S 30% 530-0.35 28 Day										
	Sample 1				Sample 2				Sample 3			
	1	2	3	4	1	2	3	4	1	2	3	4
0	29.9	27.8	27	29	30	30.4	28	27.9	28.9	27.2	24.1	24.7
10	29.7	29.5	26.8	28.9	29.6	29.9	26.8	27.4	27.7	27.4	24.4	24.1
20	29.2	29.3	25.5	28.3	29.7	30.7	26.2	26.8	28	27.5	23.5	24.2
30	28.6	29.5	25.6	27.5	29.4	30.4	27.1	26	27.3	26.1	23	23.5
40	28.2	28	25.7	27.7	29.7	29.8	27.7	25.5	26.8	25.4	23.3	23
60	28.2	28.6	24.8	26.1	28.5	30	26.7	24.9	26.4	25.2	22.3	21.8

Time of Measurement (Min)	Mix ID	S 30% 530-0.45 28 Day										
	Sample 1				Sample 2				Sample 3			
	1	2	3	4	1	2	3	4	1	2	3	4
0	20.5	26	19.7	21.6	20.6	20	22	21.7	24.5	25.4	21.3	23.9
10	15.8	22.3	20.5	21.2	18.3	21	21	19	22	20.3	19.4	21
20	15.5	18.3	16.3	16.1	15	14.6	14.2	15.8	19.2	17	19	16.3
30	14.5	15.2	14.5	15.4	14.8	14.1	14.3	15	14.8	15.7	15.5	15.3
40	14.6	14.5	14.4	15.7	14.5	13.9	14.3	14.8	15.6	15.7	16.3	15.8
60	14.2	14.2	13.6	15.6	14	14.2	14	14.4	14.5	15.3	15.5	14.9

Time of Measurement (Min)	Mix ID	SF 7.5% 430-0.35 28 Day										
	Sample 1				Sample 2				Sample 3			
	1	2	3	4	1	2	3	4	1	2	3	4
0	96.5	105	90.5	94.5	108	100	118	111	105	115	108	108
10	94.3	102	87.2	90.7	107	98.3	117	109	101	104	107	106
20	93.8	97.8	88.3	90.4	107	95.7	114	106	98.6	104	103	101
30	93.1	97.5	86.7	89.2	103	92.4	112	106	97.4	102	102	99.2
40	91.6	96.9	85.7	88.1	101	94.5	111	103	94.8	101	99	96.6
60	87.6	93.2	87.6	86	97.1	89.9	107	98.4	92.8	95.5	97.2	96

Time of Measurement (Min)	Mix ID	SF 7.5% 430-0.45 28 Day										
	Sample 1				Sample 2				Sample 3			
	1	2	3	4	1	2	3	4	1	2	3	4
0	56	56.8	53	55.9	44.3	42.1	46.5	44.5	48.9	52	50.2	53.1
10	46.7	47.3	43.3	46.6	45.3	43.6	46.2	42.5	50	51.8	49.3	51.3
20	46.3	47.3	43.9	46.2	44	40.9	43.9	41.5	48.6	48.5	48.8	50.3
30	43.1	46.4	43.6	43	45.1	42	45.4	41.3	49.3	48.4	47.6	50.9
40	45	46	42.5	45.1	44.6	41.9	45	41	48.3	49.1	49	50
60	44.6	45.8	42.1	45	44.2	41.2	44	41.3	48.4	48.7	48.5	49.4

Time of Measurement (Min)	Mix ID	SF 7.5% 530-0.35 28 Day										
	Sample 1				Sample 2				Sample 3			
	1	2	3	4	1	2	3	4	1	2	3	4
0	92.7	90.1	86.7	91.5	97.4	101	92.9	94.5	94.5	93.9	88.6	99.1
10	92.5	90.1	86.2	91	95.4	101	91.9	93.2	92.4	92.8	87.2	97.1
20	90.2	89.8	84.1	90.8	95.3	98.2	91.7	93.1	90.3	92.2	85.7	96.2
30	88.4	89.3	83.8	89.7	94.2	97.8	90.3	92.2	90.3	88.8	83.4	95.3
40	88.2	88.2	82.5	88.1	92.3	96.7	90.4	92	89.5	87.5	83.1	85.5
60	86.2	87.1	80.5	86.1	91.2	96.4	90.1	91.5	88.4	86.4	82.1	93.1

Time of Measurement (Min)	Mix ID	SF 7.5% 530-0.45 28 Day										
	Sample 1				Sample 2				Sample 3			
	1	2	3	4	1	2	3	4	1	2	3	4
0	49.5	45.8	45.9	48.1	41.4	50	48.4	49.2	48	49.5	51.4	46.1
10	49.5	45.9	46.7	49.1	43.8	50.8	47.3	46.4	47.7	49.6	50.8	47.9
20	47.2	45	44.6	49.1	45.8	49.6	47.6	47.1	46.4	49.5	50.1	46.9
30	46.7	44.6	45.2	48.9	44.1	49.3	47.2	45.8	46.7	49.4	49.1	46.4
40	45.9	44.5	44.8	49	45.5	49.5	46.7	47.1	46.3	49.8	48.8	44.9
60	45.8	42.9	44.9	47.7	44.2	49.5	46.5	46.6	46	49.4	48.5	45.6

Time of Measurement (Min)	Mix ID	S 45% 430-0.35 28 Day										
	Sample 1				Sample 2				Sample 3			
	1	2	3	4	1	2	3	4	1	2	3	4
0	48.2	48.2	49.7	54.8	45.6	48.5	49.7	49.1	54.4	51.9	52.9	53.6
10	48.6	47.2	49.8	54	44.8	49	49.1	48.2	55.2	51.6	52.8	54.3
20	49	48.8	48.9	52.4	45.2	47.4	47.7	48.2	53.4	51.5	53.4	54.5
30	48.8	48.4	48.7	51.6	43.8	48.7	49	49.5	52.9	52.6	53.4	54.2
40	48.6	46.8	48.8	53.6	43	48	48.9	49.4	52.9	52.2	52.2	54.9
60	47.5	45.6	47.5	52.7	42.3	48	47.5	48.8	54	50.5	51.9	54.2

Time of Measurement (Min)	Mix ID	S 45% 430-0.45 28 Day										
	Sample 1				Sample 2				Sample 3			
	1	2	3	4	1	2	3	4	1	2	3	4
0	31.9	33.8	34.5	32	32	29.6	30.2	33.9	35	33.4	33.4	33.7
10	32.1	33.7	32.8	29.7	32.8	31	31.1	34	34.8	32.3	33.2	34
20	31.6	32.9	33	30.2	33.8	30.1	31.1	32.3	34.6	31.6	31.8	34.7
30	31.9	33.1	33.3	29.3	32.2	29.4	30.4	34.2	35	32.1	31.6	34.4
40	31	32.8	34.2	30.1	31.4	29.5	29.6	32.6	35.2	31.3	31.4	34
60	30.9	32.5	33	30	31.8	29.8	29.5	32.5	34.5	31.3	31.5	33.8

Time of Measurement (Min)	Mix ID	S 45% 530-0.45 28 Day										
	Sample 1				Sample 2				Sample 3			
	1	2	3	4	1	2	3	4	1	2	3	4
0	27.8	25.2	28	25.7	26.7	28	29.1	29.4	28.2	24.9	30.4	28.1
10	27.3	25.7	28.3	25.5	26.9	27.1	29.1	28.8	29.5	27.6	28.4	29.8
20	28.4	25.6	28.1	26.1	27.3	27.1	28.9	28.3	28	27	27.2	27.1
30	28.9	26	28.2	26.2	27.2	27.6	28.6	27.8	27.4	26.7	27.4	26.1
40	29	25.3	27.6	25.8	26.6	27	28.6	27	27.3	26.6	27	26.4
60	27.5	25.4	28.2	26.2	26.8	27.1	27.5	26.9	28	26.5	27.2	26.2

Time of Measurement (Min)	Mix ID	S 45% 530-0.35 28 Day										
	Sample 1				Sample 2				Sample 3			
	1	2	3	4	1	2	3	4	1	2	3	4
0	41.5	41.3	40.6	42	41.4	40.9	37	44	41.4	42.2	41.2	42
10	41.3	40.8	39.9	41.4	42	41.6	38.8	42.3	41.2	41.9	40	39.6
20	39.9	40.5	39.4	39.4	41.3	41.2	38.4	42.5	41	41.1	39.7	40.4
30	39.8	40.6	38.8	41	40.2	41.3	38	41	40.5	40.3	39.8	38.5
40	39.6	39	38.5	41.3	39.7	40.8	38.6	40.9	39.9	40.1	38.8	38.7
60	39	39.3	37.5	40	39.7	40.2	36.1	41	39.9	40	38.5	39

Time of Measurement (Min)	Mix ID	FA 45% 430-0.35 28 Day										
	Sample 1				Sample 2				Sample 3			
	1	2	3	4	1	2	3	4	1	2	3	4
0	44	45.5	45.4	43.6	42	43.8	40.5	40.6	44.8	44	44.2	47.4
10	41.8	48	46.2	44	42	43.3	40.3	40.5	44.7	42.7	44.5	45.2
20	42.5	48	44.8	43.2	41.5	41.8	39.8	39.9	45.8	42.8	45.4	45
30	41.9	46.6	44.5	42.9	41.3	41.1	38.8	39.3	43.3	41.9	44.5	44.9
40	41.8	47.5	44.4	42.7	40	39.5	37.9	37.8	43.5	41.6	41	42.9
60	40.9	46.2	44.2	42.9	39.9	39.9	37.4	38.3	43.3	39.6	41.2	42.8

Time of Measurement (Min)	Mix ID	FA 45% 430-0.45 28-Day										
	Sample 1				Sample 2				Sample 3			
	1	2	3	4	1	2	3	4	1	2	3	4
0	28.6	26.8	26.7	27.2	29	27.5	23.7	23.7	25.1	26.7	26.3	25.3
10	28.5	26.6	26.7	27	28.8	28	24	26.3	25.9	26.8	26.4	24.3
20	28.3	26	26.5	26.5	28.6	27.7	24.8	24.1	26	26.8	26.5	24.1
30	28.2	26	26.2	26.4	29	27.5	24.6	23.8	24.7	26.7	24.8	23.9
40	27.9	26.4	26.2	26.1	28.3	27.5	24.1	23.7	24.9	26.5	25.9	23.7
60	27.4	26	26.5	25.4	28.4	27.4	24.3	22.5	25.1	26.1	26.2	24

Time of Measurement (Min)	Mix ID	FA 45% 530-0.35 28 Day										
	Sample 1				Sample 2				Sample 3			
	1	2	3	4	1	2	3	4	1	2	3	4
0	32.4	32.3	33.5	30.8	29.8	31	32	30.2	30.8	32	37.1	31.8
10	34.2	33.8	33.5	30.3	30.2	31.1	32.5	31	31	32.3	32.6	31.5
20	33.9	33.7	33.4	30.8	30.9	31.5	33.2	31.7	31.9	32.3	32.8	32.5
30	33.7	33.5	33.8	31.1	30.6	31.5	33.2	31.6	31.4	32.2	32.7	32.8
40	33.5	33.5	32.8	31.6	30.5	31.4	33.7	32.5	31.5	31.5	32.8	32.7
60	33.5	33.7	32.8	30.7	31.3	31.5	32.7	30.9	31.7	31.8	32.7	32.5

Time of Measurement (Min)	Mix ID	FA 45% 530-0.45 28 Day										
	Sample 1				Sample 2				Sample 3			
	1	2	3	4	1	2	3	4	1	2	3	4
0	23.5	24.3	24.6	23.1	23.5	22.5	21.6	22.1	20.5	24.2	23.4	24.5
10	23.3	24	24.5	23.4	23.1	22.1	21.4	22	20.4	24	23	24.4
20	23.5	23.5	25.1	22.8	22.8	22	21.1	21.5	19.8	23.9	22.5	24.3
30	23.2	23.7	24.1	22.7	23.5	21.7	21	21.6	19.7	23.2	22.5	24.1
40	22.9	23.6	23.5	22.6	23.2	21.6	20.7	20.8	19.1	23	22.3	23.6
60	22.8	23.2	22.8	21.7	22.5	21.2	20.6	20.4	18.8	22.5	21.7	23.3

Time of Measurement (min)	Mix ID	FA 15% 430-0.35 90 Day						
	Sample 1				Sample 2			
	1	2	3	4	1	2	3	4
0	44.5	43.9	40.8	40	40.4	44.2	40.2	43.1
10	44.6	43.2	40.2	39.7	40.1	44.6	40.5	43.2
20	42.9	43.2	40.2	41.7	40.5	44.1	40.4	42.7
30	43.7	43.6	39.1	41.9	40.3	44.8	39.9	40.9
40	43.5	44.3	39.3	40.2	40.4	43.3	40	41.4
60	42.5	44.3	38.1	39.2	38.9	42.5	39.1	41.7
Time of Measurement (min)	Sample 3				Sample 4			
	1	2	3	4	1	2	3	4
0	45.6	46.1	40.1	41.2	42.7	43.6	45.6	42.5
10	44.7	46.2	40.9	41	42.2	43.4	45.1	42
20	44.8	45.1	40.9	41	42.5	44.7	45.1	42.2
30	43.3	46	38.8	39.9	41.6	43.6	43.9	40.5
40	44.4	45.8	39.4	39.5	41.9	43.4	42.1	39.1
60	43	45.5	39.3	39	40.4	42.3	43.6	38.5

Time of Measurement (min)	Mix ID	FA 15% 430-0.45 90 Day						
	Sample 1				Sample 2			
	1	2	3	4	1	2	3	4
0	29.5	29.8	30.2	28.1	31.5	30.8	30	32.5
10	29.2	29.8	28.9	27.8	29	29.2	32.2	30.6
20	28.5	31.1	28.5	28.3	31.1	29.8	29.1	31.9
30	28.6	29.1	29.3	27.9	30.3	30.8	28.4	32.2
40	28.7	29.2	27.5	28.4	31.6	30.1	29.6	31.1
60	28.4	27.4	27	28	30.9	29.6	29.3	31.2
Time of Measurement (min)	Sample 3				Sample 4			
	1	2	3	4	1	2	3	4
0	33.2	31.5	39.6	31.1	32.8	30.2	32.8	30.6
10	30.5	32.5	30.4	34.2	29.1	28.4	31.4	32.5
20	32.2	30.4	32.1	31	30.5	28.1	28.3	30.4
30	31.1	30.6	31.7	33.8	33	31.8	29	29.7
40	31.5	29.9	31.5	30.5	31.1	29	28.6	31.9
60	31.8	30.9	31.9	29.6	31.2	30	27.2	30.1

Time of Measurement (min)	Mix ID	FA 30% 430-0.35 90 Day						
	Sample 1				Sample 2			
	1	2	3	4	1	2	3	4
0	81.4	80.8	79.4	79.1	78.7	87.3	87.3	84.5
10	78.5	73.7	75.7	75.7	74.6	86.2	86.2	81.9
20	80	76.1	75.8	73	76.8	83.5	83.5	82
30	75.1	73.5	77.5	71.6	75.8	82	82	82.8
40	77.8	75.2	77.1	77.8	77.6	81.5	81.5	80
60	73.8	71.9	71.6	70.7	70.2	79	79	82.1
Time of Measurement (min)	Sample 3				Sample 4			
	1	2	3	4	1	2	3	4
0	82.5	86.9	89.9	82.1	90.5	87	95.6	89
10	84.5	84	88.1	80.7	88.1	83.7	84.6	83
20	79.5	85.4	88.9	82.1	94	83.2	82.7	82.8
30	79.1	82.7	88	80.4	86.7	83.7	84.7	82.8
40	74.7	78.3	84	79.7	84.4	84	86	83.2
60	81.6	80.8	83.2	74.8	81.5	80.7	82	79.1

Time of Measurement (min)	Mix ID	FA 30% 430-0.45 90 Day						
	Sample 1				Sample 2			
	1	2	3	4	1	2	3	4
0	57.5	63.8	56.4	56.5	50.4	52.3	51.7	61.3
10	58.6	62.4	56.6	56	48.7	52.1	52.1	59.4
20	55.4	61.9	56.7	55.2	49.6	51.5	51.9	58.2
30	56.1	61.2	56.1	55.3	47.8	51	52.3	58.5
40	53.6	61.6	56	54.1	48.3	50.7	51.8	58.6
60	54.3	60.2	53.7	53.6	48.2	50.8	50.5	57.6
Time of Measurement (min)	Sample 3				Sample 4			
	1	2	3	4	1	2	3	4
0	49.5	51.1	53.7	52.2	51.1	53.2	55.8	53.6
10	49	51.2	53.3	51.6	50.3	52.5	54.6	53.2
20	48.9	51.2	53.7	51.1	50.3	52.6	54.4	53.1
30	48.1	49.8	53.5	51.2	49.3	52.5	54.6	53
40	48.6	50.2	52	50.2	50.4	52.5	53.8	52.7
60	47.6	48.8	52.4	50.9	48.4	51.9	53.9	52

Time of Measurement (min)	Mix ID	FA 15% 530-0.35 90 Day						
	Sample 1				Sample 2			
	1	2	3	4	1	2	3	4
0	42.8	40.2	43.7	46.6	42.4	43.8	45.5	43
10	42	40.5	42.4	42.8	40.5	42.2	41	41.8
20	42	38.1	40.2	42.6	43.6	43	43	40.9
30	42.5	39	40	41.9	39.9	41.3	40.5	42.8
40	42	38.4	39.2	41.3	41.3	41	39.3	40.5
60	41.5	38.4	40.7	40.8	40	41.5	41.3	40.9
Time of Measurement (min)	Sample 3				Sample 4			
	1	2	3	4	1	2	3	4
0	40.2	41.2	47.5	37.6	39	46.3	42.2	38.5
10	39.7	41.5	44	37.4	40.4	47	42.1	37.8
20	41.3	42.2	40.4	39.4	40.5	44.3	42.1	37.5
30	38.5	40	42.5	39.8	39.1	47	42.2	38
40	40.1	39.8	41	38.5	38.7	44.7	42.4	37.3
60	37.5	40.3	41.5	38	38.4	43.3	43	39.1

Time of Measurement (min)	Mix ID	FA 15% 530-0.45 90 Day						
	Sample 1				Sample 2			
	1	2	3	4	1	2	3	4
0	23.5	26.5	26.6	21.3	21.3	23.9	22.2	24
10	23.7	26.3	27.6	21	21.2	24.1	23	25
20	23.3	25.8	27.4	20.5	19.8	23.6	22.6	23.7
30	23.1	26	27.5	21.3	20.5	24	23	24
40	23.5	25.4	27	20.4	20.2	23.5	22.6	23.7
60	23.3	25.7	27.5	20.6	20.7	24	22.2	24.1
Time of Measurement (min)	Sample 3				Sample 4			
	1	2	3	4	1	2	3	4
0	24.5	23.4	22.1	23.9	22.6	24.3	23.9	21.7
10	24.1	23.7	22.5	23.8	22.3	24.6	24.5	23
20	24.1	23.7	22.4	23	22.1	23.8	23.7	21.2
30	24	24.2	22.5	23.8	21.8	24.4	24	22.5
40	24.1	23.2	22	23.6	22.1	23.5	23.5	21.8
60	24.4	23.5	22.5	22.9	22.4	23.5	23.5	21.9

Time of Measurement (min)	Mix ID	FA 30% 530-0.35 90 Day						
	Sample 1				Sample 2			
	1	2	3	4	1	2	3	4
0	69.9	77.2	75.2	68.6	75.9	71.2	76.2	75.7
10	70.3	76.2	77.2	68.4	75.2	71	76.7	74.3
20	69	75.9	77.9	68.6	75.2	66.9	75.5	72.7
30	72	76.1	78.2	69.2	75	68.4	74.1	73
40	69.9	76.1	78.1	68.9	75.4	71.7	73.2	72.9
60	69	75.9	73.5	67.6	75	72.5	75.4	72.6
Time of Measurement (min)	Sample 3				Sample 4			
	1	2	3	4	1	2	3	4
0	73.1	75.6	74	76.2	78.5	76.8	69.3	77.7
10	73.8	75.9	71.1	74.9	77.7	75.8	72.7	76.6
20	74.6	74.1	69.7	74.1	75.5	73.8	73.1	76.7
30	75.2	76.1	69.4	72.8	78.4	75	75.9	76.1
40	73.6	76.7	65.5	72.6	76.1	75.4	73.7	76.2
60	73.1	74.6	68.8	70.7	74.4	75.3	70	74.1

Time of Measurement (min)	Mix ID	FA 30% 530-0.45 90 Day						
	Sample 1				Sample 2			
	1	2	3	4	1	2	3	4
0	48	44.9	43	48.5	45.4	46.3	44.5	44.4
10	47.8	44.3	43.1	48	44.7	47.2	43.5	44
20	47.5	43.5	43	48	44.7	45.8	44.6	41.8
30	47.1	43.4	43	47.8	43.1	43.9	42.9	41
40	47	43.5	40.5	47.5	43.8	44.5	43.9	40.3
60	46.8	42.5	42	46.7	43.6	44.6	42.4	41.6
Time of Measurement (min)	Sample 3				Sample 4			
	1	2	3	4	1	2	3	4
0	41.5	44.2	44.9	41	39	42	41.1	40.7
10	41.33	44.2	44.4	41.8	39.3	41.8	40	40
20	40.2	43	45	41.5	37.5	41.1	41.2	41
30	40.1	42.5	44	39.6	38	40.5	40	40.3
40	40	40	43.9	39.2	38	40.6	39.9	39
60	39.3	40.8	43.3	38.4	37	40.1	38.9	38.4

Time of Measurement (min)	Mix ID	S 15% 430-0.35 90 Day						
	Sample 1				Sample 2			
	1	2	3	4	1	2	3	4
0	35.2	36	35.7	33.7	34.3	34.2	35	36.7
10	34.3	35.2	33.1	33.1	33.8	34.2	33.6	36.8
20	33	34.5	36.3	32.8	32	34.2	35	36.5
30	34.5	33.6	34.7	33.3	34.6	32.7	35.4	36.1
40	34.8	34.6	34.6	33.1	33.1	32.5	33.5	36.7
60	32.2	33.9	34.3	32.1	32.4	32.4	35	36.8
Time of Measurement (min)	Sample 3				Sample 4			
	1	2	3	4	1	2	3	4
0	36.7	39.3	35.1	37.2	33	35.6	35.1	32.6
10	37.7	38	34.6	36.9	31.6	36.1	34	32.5
20	38.3	38.2	36.5	36.5	33	36.4	32.4	33.7
30	38.7	38.1	35.1	35.9	32.7	35.8	32.8	33.4
40	37.8	38.2	34.2	34.3	32.7	36.4	33.5	33.2
60	36	37.9	33.9	35	32.1	34.8	31.3	31.2

Time of Measurement (min)	Mix ID	S 15% 430-0.45 90 Day						
	Sample 1				Sample 2			
	1	2	3	4	1	2	3	4
0	20	19	19	19	19.6	20	18.9	20.7
10	19.6	17.9	18.9	19.4	19.4	20.2	19	20.1
20	18.1	18	18.7	19.5	19.1	19.1	18.7	21
30	17.9	18.3	18.5	19.7	18.8	19.4	18.2	20.5
40	18.2	18	18.7	20	19.1	19.5	18.5	20.3
60	17.6	17	18	18.9	18.6	19.1	18.1	19.6
Time of Measurement (min)	Sample 3				Sample 4			
	1	2	3	4	1	2	3	4
0	22.4	21.5	21.3	21.8	18.5	19.4	18	17.3
10	18.9	19.1	17.6	17.6	18.4	18.6	18	17.5
20	19	18.9	16.8	17.6	18.3	18.9	17.2	17.6
30	18.9	19	17.2	17.5	18.2	18.4	17.9	17
40	19	19.6	16.8	17.6	17.5	18	17.5	17.3
60	20	18.6	16.8	17.3	17.7	18.3	17.9	16.9

Time of Measurement (min)	Mix ID	S 30% 430-0.35 90 Day						
	Sample 1				Sample 2			
	1	2	3	4	1	2	3	4
0	53.6	50.9	55.5	51.6	53.8	54.6	54.7	56.5
10	54.9	51	54.1	51.6	54.5	56.5	54.2	56.1
20	52.7	50	53.5	52.9	53.5	55.7	52.5	55.9
30	52.6	50.8	53.7	52.2	53.7	54.5	52.6	55.4
40	51.7	51	51.5	51.2	52	55	53.6	55
60	52.6	50.2	50	50.8	52.2	52	53.6	52.6
Time of Measurement (min)	Sample 3				Sample 4			
	1	2	3	4	1	2	3	4
0	48.1	55.3	51.8	49	51.5	50.2	51.1	57.2
10	49.9	56	50.9	50	53.3	49.6	52.2	54.2
20	48.2	57.1	52	49.4	54.8	48.2	52.7	50.6
30	48.3	54.8	52.4	47.9	52	48.7	53.6	52.1
40	46.4	54.5	50.3	49.1	52.5	46.2	51.4	49.5
60	42.2	52.8	48.7	46.1	51.6	45.8	49.6	49.1

Time of Measurement (min)	Mix ID	S 30% 430-0.45 90 Day						
	Sample 1				Sample 2			
	1	2	3	4	1	2	3	4
0	31.4	35.7	36.6	35.2	36	35	33.6	31
10	30.6	35.8	35.4	34.5	35.7	35.4	33.3	32.2
20	31.4	35.2	36.4	34.5	35.2	35	33.2	31.3
30	30.8	35	35.8	34.1	34.5	35	32.9	30.7
40	30.8	35.2	35.9	34.3	34.5	35.3	32.7	30.3
60	30.1	33.8	35	33.3	30.9	33.8	34.3	31.8
Time of Measurement (min)	Sample 3				Sample 4			
	1	2	3	4	1	2	3	4
0	33.2	31	32	32	32.4	31.7	30.5	31.3
10	35.3	32.9	31	31.8	31.4	31.6	29.4	29.6
20	34.2	33.1	31.4	32.3	32	30.7	29.6	29.4
30	33.4	32.8	30.7	31.7	31.4	30.7	29.5	28.7
40	33.5	31.3	30.7	31.7	31.6	30.4	28.5	28.5
60	31.7	30.2	30.2	30.6	30.6	29.9	28.2	28.4

Time of Measurement (min)	Mix ID	S 15% 530-0.35 90 Day						
	Sample 1				Sample 2			
	1	2	3	4	1	2	3	4
0	37.9	32.4	30.9	32.2	28.8	30.4	29.4	30.2
10	37.3	31	30.9	31.5	28.8	30.5	28.7	30.5
20	37.3	31.2	30.5	31.3	28	30.7	28.5	30.4
30	37.3	31.2	30.4	31.2	28.1	30.5	27.8	30.5
40	37.2	31.5	30.3	31.2	28.3	30.1	27.8	30.4
60	36	31.2.	30.2	31.1	28.1	29.2	27.5	29.1
Time of Measurement (min)	Sample 3				Sample 4			
	1	2	3	4	1	2	3	4
0	28.2	27	28	31	30.6	34	30.7	32
10	30	27	27.9	30.8	30.6	34	30.5	31.1
20	29.9	27	27.8	30.7	30.4	33.5	30.5	31
30	29.7	27.2	27.8	30.7	29.7	32.7	30.5	31.1
40	29.6	27	27.4	29.8	29.5	32.1	30.4	31
60	28.9	26.8	27.3	29.7	29.3	32	30.1	29.9

Time of Measurement (min)	Mix ID	S 15% 530-0.45 90 Day						
	Sample 1				Sample 2			
	1	2	3	4	1	2	3	4
0	16.4	15.9	16.2	15.9	15.8	14	14.6	15.2
10	16.4	16.1	16.2	16.1	15.7	14	15	14.8
20	16.3	16.1	16.3	16.1	15.7	13.6	13.7	15.3
30	16.3	16.1	16.3	16.1	15.8	13.9	13.8	15.1
40	16.3	16	16.3	16.1	15.9	13.7	14.7	14.9
60	16.2	16	16.3	15.8	15.6	13.7	14.2	13.8
Time of Measurement (min)	Sample 3				Sample 4			
	1	2	3	4	1	2	3	4
0	14.1	15.4	15.1	14.1	14.6	15.6	13.5	14.2
10	14.3	15.7	15.1	14.3	14.2	16	12.7	14.3
20	14.3	15.9	15.1	13.9	14.7	15.1	12.8	14.2
30	14.3	15.3	15.2	13.9	14.6	14.9	13	14.2
40	14	15.8	14.8	13.9	13.9	14.7	13	14.2
60	13.8	15.4	14.9	14	14.4	14.7	12.8	13.9

Time of Measurement (min)	Mix ID	S 30% 530-0.35 90 Day						
	Sample 1				Sample 2			
	1	2	3	4	1	2	3	4
0	49.1	48.5	46.2	49	48.4	46.8	44.9	44.7
10	48.5	48.2	46.4	48.6	48.6	45.6	44.1	44.2
20	47.8	18.1	46.2	48.1	46.2	45.8	42.4	44
30	47.2	47.5	44.7	47.3	45.3	44.7	42.5	42.9
40	46.1	46.6	45.1	47.4	45.9	44.6	42.5	42.6
60	45.3	46.2	43.9	45.8	43.3	43.3	41.2	41.8
Time of Measurement (min)	Sample 3				Sample 4			
	1	2	3	4	1	2	3	4
0	44.7	47.4	38.7	40.5	42.4	43.2	43.4	46.3
10	44.3	47.2	39	39.7	42.2	42.4	42.1	45.8
20	44.2	46.7	38.7	39.3	41.7	42.2	42.1	44.1
30	43.4	46.3	38.1	39	40	41.9	41.6	44.6
40	42.9	46.2	37.6	38.8	40.9	41.4	41.2	43.2
60	42.5	45.3	36.8	38	40	41.2	40.8	42.6

Time of Measurement (min)	Mix ID	S 30% 530-0.45 90 Day						
	Sample 1				Sample 2			
	1	2	3	4	1	2	3	4
0	26.4	26.3	26.2	24.2	23.5	25.6	27.9	27
10	26.3	25.9	26.2	24.3	23.2	25	27.5	26.8
20	25.3	25.8	26.1	24.1	23.2	24.8	27.3	26.8
30	25.4	25.8	25.8	24.2	23.3	24.3	27.3	26.6
40	25.4	25.5	25.5	23.8	23.1	24.3	27.2	26.5
60	24.4	24.9	24.6	23.5	22.7	24	26.9	26.3
Time of Measurement (min)	Sample 3				Sample 4			
	1	2	3	4	1	2	3	4
0	25.9	22.4	23.7	23.4	26	23.5	25.2	25.2
10	25.5	22.1	23.5	23.2	25	23.6	25	24.5
20	25.4	21.9	23.3	23.1	25.5	23.6	24.6	23.8
30	25.2	21.6	23.3	22.8	25.5	23	24.4	23.8
40	24.9	21.5	22.9	22.5	24.8	23.4	24.1	23.8
60	24.5	19.9	22.9	22.7	24.9	23.1	23.8	23.5

Time of Measurement (min)	Mix ID	SF 7.5% 430-0.35 90 Day						
	Sample 1				Sample 2			
	1	2	3	4	1	2	3	4
0	174.5	150	181	158	182	186	192	192
10	173.8	146	180	168	181	180	195	187
20	171	144	173	158	179	180	192	185
30	181.8	143	161	155	182	169	193	185
40	162.2	139	159	156	173	166	188	184
60	163.3	140	155	152	169	170	183	178
Time of Measurement (min)	Sample 3				Sample 4			
	1	2	3	4	1	2	3	4
0	189	181	192	186	169	173	173	169
10	184	179	179	179	162	163	167	165
20	176.6	176	183	181	160	167	166	167
30	177	175	180	176	161	158	163	165
40	182	174	175	175	163	158	165	161
60	173	170	175	179	154	156	156	153

Time of Measurement (min)	Mix ID	SF 7.5% 430-0.45 90 Day						
	Sample 1				Sample 2			
	1	2	3	4	1	2	3	4
0	78.8	92	81.7	81	80.5	81.8	80.5	80.4
10	75.8	82.3	78.4	77.4	78.2	80.5	79.5	77.4
20	73.2	81.5	74.2	75	72.4	74.7	78.6	74.8
30	72.3	81	77.3	75.3	73.8	77	77.2	75.6
40	72.5	80	77.8	73.9	72.5	73.1	75.5	74.7
60	71.6	76.9	70.8	72.8	70.4	70.2	76	71.3
Time of Measurement (min)	Sample 3				Sample 4			
	1	2	3	4	1	2	3	4
0	72	77	78.2	79.1	84.5	82.4	78	92
10	67.3	73.8	73.4	78	79.9	78.4	77	91.2
20	67	68.3	69.2	77.9	80	75.2	72.3	86
30	66	75.2	68	75.5	77.4	76.2	71.9	81
40	65.1	68	68.1	74	76.6	75.4	73.8	78.8
60	64	67.3	67.4	71.8	74.2	75	70	74.3

Time of Measurement (min)	Mix ID	SF 7.5% 530-0.35 90 Day						
	Sample 1				Sample 2			
	1	2	3	4	1	2	3	4
0	169.9	142	134	156	157	151	153	157
10	170.2	141	135	152	157	150	149	155
20	162.7	140	132	151	156	151	148	153
30	161.2	139	131	149	155	146	148	152
40	160	136	128	149	153	149	145	151
60	157.5	136	127	143	150	144	144	148
Time of Measurement (min)	Sample 3				Sample 4			
	1	2	3	4	1	2	3	4
0	146	153	149	146	162	157	156	156
10	145	153	144	143	162	156	155	155
20	143	150	144	142	159	153	156	153
30	141	148	141	142	160	151	153	155
40	139	144	140	139	157	151	150	151
60	137	145	136	136	154	147	148	149

Time of Measurement (min)	Mix ID	SF 7.5% 530-0.45 90 Day						
	Sample 1				Sample 2			
	1	2	3	4	1	2	3	4
0	75.8	79.6	77	67.5	76.9	76.5	81.2	78.5
10	76.6	79.1	79.4	66.2	74.1	77.4	80.1	79.5
20	74.4	76.1	76.8	65.7	75	78.4	80.2	78.2
30	73.6	78.3	77.9	64.3	74.1	74	79	78
40	72.2	75.5	75.1	64.6	72.8	73.2	78.2	77.8
60	73.3	75.2	72.5	63.8	70.7	72.5	74.9	76.5
Time of Measurement (min)	Sample 3				Sample 4			
	1	2	3	4	1	2	3	4
0	83.1	77.7	80.8	79.8	75.8	72.9	73.7	79.9
10	80.4	76.3	78.9	79.1	75.8	73.7	74	78.5
20	78	75.3	77.7	77.3	74.7	70	72.5	78
30	78.7	76.5	74.1	77.7	73.3	71	70.2	77
40	77.7	73.6	76.7	76.5	73.5	68.6	69.3	75.7
60	75.8	74.9	74	76.9	71.6	68.7	69.5	74.9

Time of Measurement (min)	Mix ID	S 45% 430-0.35 90 Day						
	Sample 1				Sample 2			
	1	2	3	4	1	2	3	4
0	70	71	75.8	76	75.6	74	76	77
10	65	68	75.5	74	73	73.8	73.3	75
20	64.8	67	75	71.8	71.6	73	72.7	70
30	63.4	68.5	75.4	71	72	71.2	73.2	69.2
40	61	71.5	72	70	71	71.8	73.5	71.3
60	64	71	69.2	68.1	72.2	70	72	71.2
Time of Measurement (min)	Sample 3				Sample 4			
	1	2	3	4	1	2	3	4
0	77.2	78	73	76	77	72	78	79.5
10	74	75	73	75.8	73	71	77	74.1
20	73	73.5	72.8	77	71.5	70	75.5	73.8
30	70.3	73	71.5	76.1	73	68	74	75
40	76	75	70.2	76	69	70	73	70.2
60	72.8	73.2	73.2	70.5	70.7	67.6	74	70.9

Time of Measurement (min)	Mix ID	S 45% 430-0.45 90 Day						
	Sample 1				Sample 2			
	1	2	3	4	1	2	3	4
0	51.2	51	47.6	46	51.4	55.2	53.5	53.3
10	51.5	51.8	49.2	46.9	52.5	55.8	54.5	53.9
20	53.2	52.7	49.5	46.1	53.7	55.3	55.4	54.1
30	51.1	52	50.4	48.1	51.2	55.6	54.6	54.9
40	51.4	51.1	48.1	48.2	51.4	55.6	54.4	54.4
60	51.4	53.4	50.5	46.9	50.3	55.6	54.1	55.1
Time of Measurement (min)	Sample 3				Sample 4			
	1	2	3	4	1	2	3	4
0	52.5	59	50.2	50.6	52.5	53	48.8	47.6
10	52.3	58.7	51.4	53.6	55.7	55.4	49.2	48.3
20	53.8	60.1	52.1	54.1	53.8	55.1	50.7	48.7
30	52.7	59.8	51.7	53.5	52.8	54.5	49.5	49.7
40	51.9	60.6	51.1	52.7	52.1	54.4	48.8	48.4
60	50.8	60.4	52.1	53.3	53.8	53.6	48.4	47.8

Time of Measurement (min)	Mix ID	S 45% 530-0.45 90 Day						
	Sample 1				Sample 2			
	1	2	3	4	1	2	3	4
0	43.4	37.8	43.9	42.5	44.3	43.6	42.7	49.7
10	43.8	37.6	43.9	43.3	44.2	43.4	42.8	49.1
20	44.4	37.3	44.1	41.9	43.6	42.8	42.9	50.8
30	43	36.4	43.6	41.9	43.7	43.6	42	49
40	41.9	36.7	42.5	41.3	42.3	41.9	40.9	47.6
60	41	36.6	42.5	40.1	42.9	43.6	41.3	46.4
Time of Measurement (min)	Sample 3				Sample 4			
	1	2	3	4	1	2	3	4
0	40.4	41.6	43.2	43.3	38.6	41.7	39.2	40
10	40.3	42.5	43.5	42.6	38.4	42.3	39.8	39.4
20	40.2	40.6	43.6	43.3	38.3	41.9	40	38.9
30	38.9	40.7	42.6	42	36.6	41.2	38.6	38.3
40	36.6	38.9	42.2	42.2	37.6	41.6	38.9	37.7
60	38.4	40.6	43.6	41.3	36.5	40.9	37.3	40

Time of Measurement (min)	Mix ID	S 45% 530-0.35 90 Day						
	Sample 1				Sample 2			
	1	2	3	4	1	2	3	4
0	68.6	67.6	65	61.7	72.8	72.6	69.5	80.1
10	66.1	67	65.6	62.8	70.2	74	71	78.7
20	65.8	66	65.3	61.7	70.2	72.6	69.5	80.1
30	66.1	65.3	64.8	61.7	71	71.2	69.6	78.6
40	64.8	65.1	63.5	61.3	68.2	69.6	69.2	79.2
60	62.9	62.6	61.1	59.6	69	70	70.4	77.4
Time of Measurement (min)	Sample 3				Sample 4			
	1	2	3	4	1	2	3	4
0	68.3	74.1	71.9	65.3	65	64.2	65.2	62.3
10	67	73.7	71.1	63	65.8	64	65.8	61
20	67.5	75.4	69.6	65.7	66.5	64.5	64.1	60.1
30	66.4	73.6	69.3	64.2	64.6	63.7	63.4	60.5
40	67.5	71.2	68.4	64.3	62	62.8	63.7	59.3
60	67	69.7	66.8	63.3	64	62	61.6	59

Time of Measurement (min)	Mix ID	FA 45% 430-0.35 90 Day						
	Sample 1				Sample 2			
	1	2	3	4	1	2	3	4
0	172.2	163	162	162	157	164	170	174
10	168.3	164	164	164	157	163	170	171
20	164	161	165	165	152	161	168	171
30	165.2	159	166	166	153	157	170	170
40	162.4	157	163	163	156	158	169	168
60	162	156	159	159	154	153	165	168
Time of Measurement (min)	Sample 3				Sample 4			
	1	2	3	4	1	2	3	4
0	164	164	184	163	158	172	167	161
10	164	160	182	165	156	173	167	158
20	162	157	183	166	158	174	169	158
30	163	161	180	165	155	172	165	152
40	162	159	179	162	151	170	162	151
60	160	157	176	158	153	167	160	151

Time of Measurement (min)	Mix ID	FA 45% 430-0.45 90 Day						
	Sample 1				Sample 2			
	1	2	3	4	1	2	3	4
0	105	104	101	103	98.1	95.2	95.1	91.7
10	98.5	103	101	102	97.5	95.3	96.9	88.7
20	96.6	101	98.5	100	95.9	92	95.8	88.9
30	95.6	100	97.6	99.8	93.6	90.9	94.4	86.5
40	94.9	103	98.5	103	95.5	93.2	96.5	90.2
60	97.5	99.7	96.5	98.5	93.8	93.2	95.9	88.8
Time of Measurement (min)	Sample 3				Sample 4			
	1	2	3	4	1	2	3	4
0	99.7	102	90.6	98.6	101	95.1	108	94.1
10	98.9	101	88.8	101	97.7	93.6	104	92.8
20	96.9	98.5	88.1	98.3	95.7	94.1	104	93.2
30	96.2	97.4	89.4	98.4	98.2	94.5	104	92.8
40	91.5	98.1	91.6	98.1	100	95.1	99.7	91.3
60	89.1	97.7	90.3	96.1	96.9	91.2	99.5	91.1

Time of Measurement (min)	Mix ID	FA 45% 530-0.35 90 Day						
	Sample 1				Sample 2			
	1	2	3	4	1	2	3	4
0	136.3	141	140	125	124	122	134	125
10	132	135	140	123	125	122	133	124
20	128.4	133	136	121	120	121	132	122
30	129.5	129	136	124	122	120	130	123
40	126.6	127	134	121	118	118	131	124
60	126.8	120	130	117	115	114	126	118
Time of Measurement (min)	Sample 3				Sample 4			
	1	2	3	4	1	2	3	4
0	134	147	130	130	141	144	150	140
10	131	144	130	124	138	142	142	137
20	129	142	127	120	135	136	144	134
30	130	138	126	120	131	135	140	136
40	127	138	122	120	131	135	141	130
60	123	133	121	116	129	139	135	126

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