Final Report

Evaluation of Concrete Treated with Surtreat TPS-II Surface-Applied Treatment

by

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Executive Summary

Surtreat TPS-II is a surface-applied treatment for concrete structures whose purpose is to improve durability under adverse exposure conditions. A laboratory evaluation was conducted to assess the applicability and effectiveness of Surtreat TPS-II when applied to existing concrete structures. The experimental program was designed to incorporate an array of tests that would illustrate the practicality and effectiveness of Surtreat TPS-II in concrete repair and rehabilitation. The testing program evaluated the effect of Surtreat TPS II on the physical and chemical characteristics of concrete specimens, as compared to a control group of untreated specimens.

The concrete properties evaluated were:

- Surface scaling resistance when exposed to deicing chemicals
- Surface abrasion resistance when exposed to sandblasting
- Impressed current
- Compressive strength
- Flexural strength
- Water absorption
- Water permeability

The laboratory testing revealed that Surtreat TPS-II improved the quality of the concrete samples tested. A summary of the range of improvement for each of the evaluated properties is provided below. Detailed results are presented in the report.

Property	**Change**
Scaling Resistance	66% to 87% lower mass loss
Abrasion Resistance	21% to 50% lower mass loss
Impressed Current	45% to 128% longer time to failure
Compressive Strength	8% to 13% increase in strength
Flexural Strength	13% to 20% increase in strength
Absorption of Water	28% to 46% decrease in water absorption
Water Permeability	27% to 38% decrease in permeability

The physical results obtained from the testing regimen of concrete samples topically treated with Surtreat TPS-II showed improvement in each of the tests conducted, indicating that the surface treatment of concrete with Surtreat can result in improvements to the physical characteristics of the concrete surface. Additionally, the testing revealed that the durability characteristics of concrete and embedded steel are vastly improved. The use of Surtreat TPS-II appears to be a viable option for the rehabilitation of concrete structures, as well as for improving the durability performance of the concrete itself.

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1 Introduction

Historically, the primary factor in the design of concrete structures has been compressive strength. The majority of structural design guides and design codes published by North American based technical organizations generally consider compressive strength as the only significant mechanical property of the concrete material. However, despite the fact that industry has focused primarily on concrete compressive strength in the design of structures, the overwhelming majority of structures experience failure due to durability-based issues.

Durability and maintenance related issues comprise the majority of expenditures for concrete structures today. A short list of the degradation processes that reinforced concrete structures may experience includes; "reinforcement corrosion, sulfate attack, alkali -silica reaction (ASR), freeze thaw attack, leaching and construction overloads" [1].

Presently, there has been a movement by infrastructure administrations to increase the service life of structures from 50 years to 100 years or more. Infrastructure officials are attempting to increase the life cycle of these structures with minimal cost to the public. Many transportation structures in service today were designed with a 50 year service life but are well over 50 years old, with insufficient resources available for replacement. Thus, it is of great importance to find ways to extend the service life of such structures.

This report describes the evaluation of a surface applied treatment (Surtreat TPS-II) designed to improve the durability related behavior of existing concrete structures in order to assess its applicability and performance for such implementation.

2 Methodology

Research involving surface treatments and their effects on Portland cement-based concretes dates back to the 1920's [2]. Despite prolonged study of surface treatments, the majority of research to date has concluded that most surface treatments simply "coat" the concrete surface without producing any physical changes within the hardened cement matrix itself. The purpose of this research was to determine whether a topically applied treatment could effect changes on the physical and chemical properties of Portland cement concrete.

3 Experimental Program

The experimental program was designed to incorporate an array of tests aimed at evaluating the practicality and effectiveness of Surtreat TPS-II in concrete repair and rehabilitation. The testing program was formulated to evaluate physical and chemical characteristics of concrete specimens treated with Surtreat TPS-II compared to a control group. Most of the tests performed in this study consisted of American Society of Testing and Materials (ASTM) standardized methods.

3.1 Concrete Mixture Parameters

The primary concrete mixture variable affecting durability is water-cement ratio. The most accepted design guide for building code requirements of structural concrete in North America is ACI 318. Therefore, this evaluation utilized two water-cement ratios, the ACI 318 requirement for severe sulfate exposure (0.45) and a "worst case scenario" (0.65). Two groups of specimens were created for each water-cement ratio, a test group of samples which were treated with Surtreat TPS-II, and a control group which was left untreated for comparison purposes. The specimen sizes and quantities varied as required by the relevant standards for the particular ASTM tests described herein. The mixture proportions in Table 1 were used to represent typical mixtures implemented in concrete industry.

Table 1: Concrete Mixture Design and Properties

Mix Design Volume = 1 m^3	A 0.45 w/cm	B 0.65 w/cm
Cement (kg/m^3)	448.3	311.8
Water (kg/m^3)	201.7	202.6
Sand (kg/m3)	617.5	730.4
Aggregate (kg/m^3)	1068.9	1068.9
Superplasticizer (Adva 100) L/m^3	0.8	0.0
Density (kg/m^3)	2336.4	2313.7
Measured Slump (mm)	140.0	165.0
Air Content %	2 - 2.5	1.5 - 2

Specimen preparation, testing, and curing were conducted in accordance with the relevant ASTM standards [3]

3.2 Evaluation Techniques

The regimen for thorough investigation and evaluation of the performance of Surtreat TPS-II applied to concrete required an array of tests. The test methods most relevant to the study of surface applied treatments for concrete materials in a relatively short period of time are:

- The scaling resistance of concrete surfaces exposed to deicing chemicals [4]
- The abrasion resistance of concrete to sandblasting [5]
- Impressed current [6]
- Compressive strength [7]
- Flexural strength
- Water absorption
- Water permeability
- Microscopic examination

Additionally, nondestructive testing (NDT) techniques were used to monitor changes in the concrete properties over time. Surface hardness was evaluated using the rebound hammer method. [9] It has been shown that stress wave based NDT techniques, including Ultrasonic Pulse Velocity (UPV) and Impact Echo (IE), are valuable for use in monitoring physical changes within concrete materials [10].

3.3 Sample Preparation

Upon completion of mixing and batching, the concrete samples were cured for 28 days unless otherwise specified in the relevant ASTM standardized test method. Following curing, the samples were allowed to dry for two weeks prior to treatment with Surtreat TPS-II. Samples in the experimental group were treated topically with Surtreat TPS-II two weeks prior to exposure or testing.

Treatment consisted of the manual application of Surtreat to the relevant test surface of all samples, with the exception of cylinder samples used in compressive strength and impressed current testing. As per the manufacturer's instructions, one gallon of Surtreat is typically used to treat 100 square feet of concrete surface area. Since the samples used for evaluation were relatively small, application in the lab was performed using a syringe, measuring the volume of treatment to the nearest milliliter (depicted in Figure 1).

Figure 1: Typical Surtreat TPS-II application procedure.

It is standard practice in the United States to use cylindrical concrete specimens for compressive strength testing. Additionally, the standard test method for impressed current testing also requires cylindrical samples. Cylindrical samples were treated by submersion in Surtreat for a period of 10 minutes per sample with w/c of 0.65. This time period was chosen once it was determined that the volume of Surtreat TPS-II absorb within 10 minutes was roughly equivalent to the volume specified by the manufacturer for treatment of a surface area equivalent to a single cylinder. The time of submersion for the sample group of 0.45 was found to be 18 minutes.

4 Test Results

4.1 Resistance to Surface Scaling

Over the past several decades, there has been considerable progress regarding understanding of the freezing phenomena in concrete materials. Despite vast research dedicated to the subject, the mechanisms of deicer salt scaling deterioration of concrete are still not fully understood [11]. Scaling is a significant problem for concrete pavements and bridge decks exposed to deicing salts. While the majority of research regarding the resistance of concrete to scaling incorporates freeze-thaw cycles, research has shown that calcium chloride deicers ($CaCl_2$) have adverse effects on concrete regardless of temperature [12].

The investigation of the performance of laboratory specimens treated with Surtreat TPS-II in comparison with control (untreated) specimens exposed to a freezing and thawing environment in the presence of a deicing chemical was intended to evaluate the surface resistance of the concrete. Reporting of results as per the ASTM standard (C 672) is solely visual, and thus qualitative, in nature. In Canada, the Ontario Ministry of Transportation (MTO LS-412) prescribes a similar testing protocol, though it includes measurement of the mass loss of concrete from the specimen surface and is thus quantitative in nature. This study employs both qualitative and quantitative results in the reporting of scaling resistance.

The procedure used for fabrication and preparation of specimens used in this experiment was performed in accordance with ASTM C 672-98. Specimen size and history were as follows:

- 3 samples of each of the 4 treatment groups, which consisted of a control group and a treated specimen group for each of the two w/c concretes, 12 specimens in total
- Sample size = 7" x 12" x 3"
- Moist cured for 14 days prior to exposure
- Ponded with 4% $CaCl_2$ Solution
- Exposed to 50 cycles of freeze-thaw

When used for evaluation of surface treatments, ASTM C 672 requires a 14-day moist curing period followed by 7 days of air curing before surface treatment. Following the application of the surface treatment, the samples are then required to be stored in air for 14 days prior to exposure to freezing and thawing cycles. Therefore, the only difference in the conditioning of samples between the Surtreat TPS-II and control groups is that the experimental group was treated 7 days after removal from moist curing. Freeze-thaw cycling of all samples was thus initiated 28 days after casting.

Immediately prior to exposure, the samples were ponded with a 4% calcium chloride solution and then placed in a freezing environment for 16-18 hours, followed by a 6-8 hour thawing period. ASTM C 672 requires the specimen surfaces to be flushed and the ponding solution changed every 5 cycles. In the interest of obtaining quantitative results, the flushed solution was collected and filtered to determine the amount of mass loss from each concrete surface. Additionally, visual ratings were recorded as per the ASTM standard requirements.

Results and Discussion

The mass loss results from the deicer salt scaling tests are shown in Figure 2. As is often the result of these tests, the damage to the concrete surface throughout the first 15-20 cycles was minimal for all of the specimens tested. However, after 20 cycles of exposure the untreated samples begin to exhibit more damage than the treated samples.

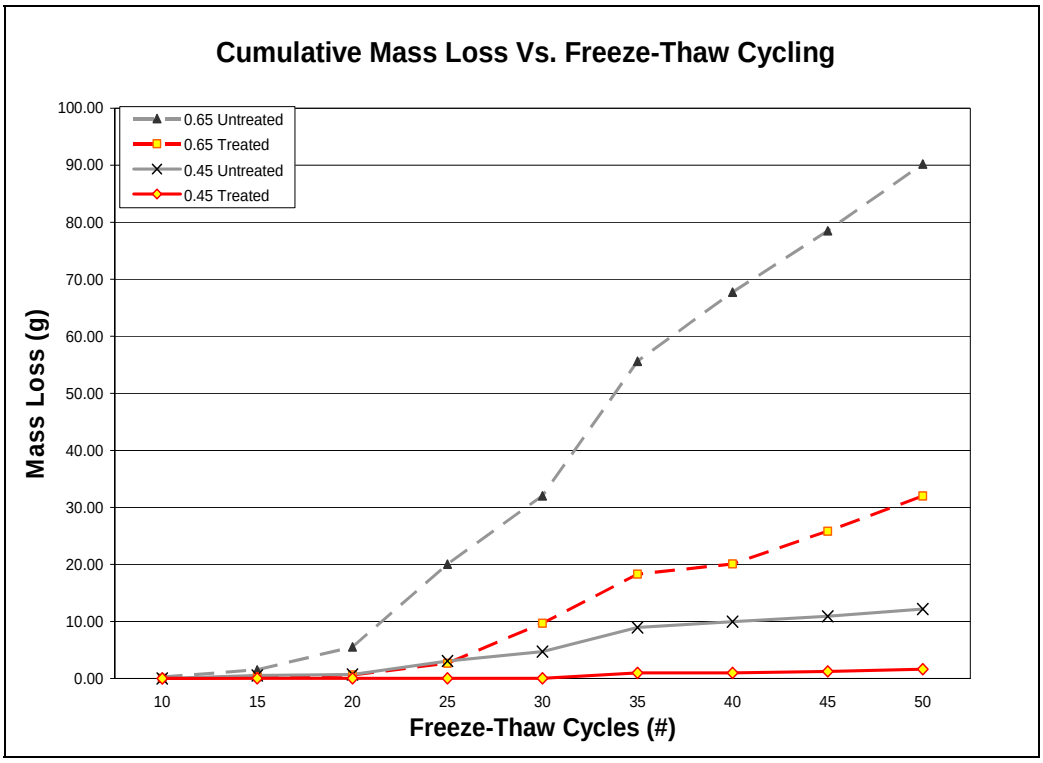

Figure 2: Mass loss values from deicer salt scaling evaluation

As shown in Figure 2, there was a significant difference in performance between the Surtreat samples and the untreated control specimens. After 50 cycles, the treated 0.45 w/c samples exhibited 87% less mass loss than the untreated samples and the treated 0.65 w/c samples exhibited 66% less damage than the untreated samples. Thus, the topical application of Surtreat to concrete was shown to reduce the damage induced by surface scaling. Figure 3 is a photograph of two 0.45 w/c specimens after exposure to 50 freeze – thaw cycles. Appendix A contains the raw data and statistical analysis. The sample on the

left is the untreated sample and the sample on the right is the Surtreat specimen. The lower w/c samples did not experience as much damage the higher w/c samples, as researchers have previously stated [11,13].

Figure 3: Untreated (left) and treated (right) samples after exposure to 50 freeze-thaw cycles.

4.2 Resistance to Abrasion

Testing of the resistance of concrete surfaces to abrasion is intended to evaluate the ability of concrete to resist attrition as experienced by concrete pavements, bridge decks, and other traffic carrying elements. ASTM C 418-98 is a standardized test method specifically designed for the evaluation of abrasion resistance of concrete by sandblasting. The test method does not specify any particular sample size or shape so it was decided that 2’ x 1’ x 2” rectangular slabs would be used for the application of a surface treatment, and subsequent exposure to sandblasting.

The sample preparation and curing regimen for these specimens was performed as per the relevant standard [3]. Upon the completion of moist curing at 28 days the treated samples were air cured for an additional 7 days prior to the application of Surtreat TPS-II. Following treatment, the samples were stored in air for an additional 6 days before being returned to moist curing for 24 hours. All of the samples for this evaluation were thus tested 42 days after casting.

Results and Discussion

The method used to determine volume loss for the sandblasted samples is unlike most other methods of sample analysis. Sandblasting the concrete surface creates an abrasion cavity, which is subsequently filled with modeling clay to determine the volume of material lost from testing. The mass of clay absent from the initial sample is then used as a quantitative value for the analysis. Figure 4 shows typical samples with clay placed in abrasion cavities.

Figure 4: Sandblasted specimens with clay placed in abrasion cavities.

$$W_c = W_i - W_f \text{ [5]} \qquad (1)$$

Where:

W_c = mass of clay needed to fill abrasion cavity

W_i = initial mass of clay

W_f = final mass of clay.

Upon determination of the specific gravity of the clay, the volume (V) of the abrasion cavities can be obtained. The surface area (A) of the abrasion cavities is then measured to obtain an abrasion coefficient A_c [5]

$$A_c = V / A \text{ [5]} \qquad (2)$$

Table 2: Abrasion resistance test results

	0.45 Treated		**0.45 Control**		**0.65 Treated**		**0.65 Control**	
	Clay	Mass (g)	Clay	Mass (g)	Clay	Mass (g)	Clay	Mass (g)
	W_i	355	W_i	380	W_i	464	W_i	461
	W_f	280	W_f	255	W_f	383	W_f	357
	W_c	75	W_c	125	W_c	81	W_c	104
V (mm^3)	42850		71416		46078		59356	
A (mm^2)	6715		5569		5983		6120	
A_c	6.38		12.82		7.70		9.70	

The data and resulting abrasion coefficients in Table 2 show that the treated samples experienced less volume and mass loss than the control samples. Additionally, the resulting abrasion coefficients are also lower than those of the control samples. The test data indicates that the application of Surtreat TPS-II to concrete can improve its resistance to abrasion.

4.3 Impressed Current Testing

The corrosion of steel reinforcement is one of the major components influencing the long-term performance of concrete structures [1]. The impressed current technique is used is by the Florida Department of Transportation, among others, to evaluate the time required to initiate corrosion of the reinforcing steel in concrete [14]. This technique allows determination of corrosion initiation in a greatly reduced time interval. The Florida Department of Transportation has standardized the impressed current test method [FM 5-522] for use in the investigation of corrosion susceptibility of concrete materials, protective coatings, rebar coatings and rebar claddings [6].

Sample preparation

A typical sample used in the impressed current test is essentially a 4" diameter concrete cylinder with a #4 rebar inserted down the center, as depicted in Figure 5. The casting procedure is similar to the casting of cylindrical samples with the exception of a rack designed to hold the rebar in place during casting and consolidation of the concrete.

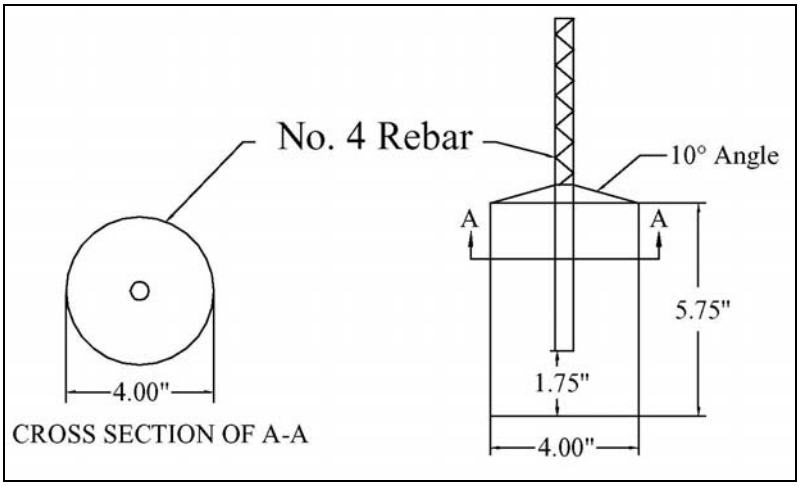

Figure 5: Schematic of a typical sample used for impressed current testing.

Following removal from their molds, the impressed current specimens were moist cured for 28 days. Upon completion of curing at 28 days the treated samples were air cured for an additional 7 days prior to the application of Surtreat TPS-II. Following treatment, the samples were stored in air for an additional 6 days before returning to moist cure 24 hours prior to testing. Therefore, the only difference in the conditioning of samples between the Surtreat and control groups is that the experimental group was treated 7 days after removal from moist curing. The samples were then partially submerged in a 5% Sodium Chloride (NaCl) solution for an additional 28 days to facilitate the initiation of corrosion activity.

Testing Procedure

The impressed current test consists of the induction of an electrical current along the reinforcing bar by connecting the rebar to a 6V DC power supply. Each sample is

connected to an individual shunt so that the current within each sample can be measured. The specimen is partially submerged in a 5% Sodium Chloride (NaCl) solution to provide a conductive medium between the sample and a second piece of rebar completely immersed in the NaCl solution. Figure 6 schematically illustrates the impressed current system used for sample testing in this experiment.

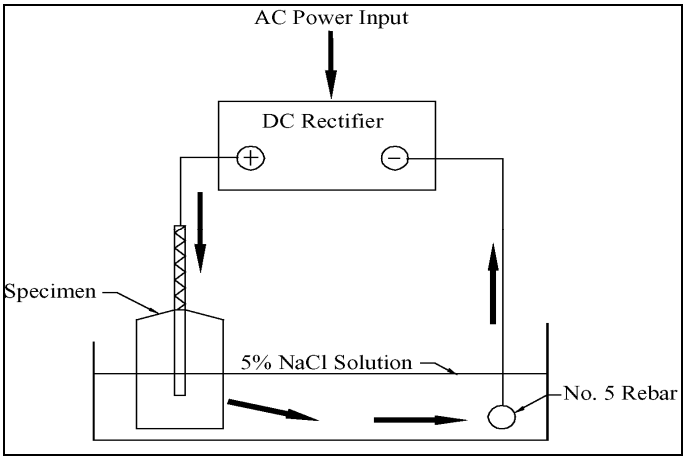

Figure 6: Schematic of impressed current test configuration.

Once the electrical circuit is complete, the sample current and voltage drop are continuously monitored until failure. Failure is defined by one of two means:

- The appearance of a visible crack in the specimen
- The detection of a sharp increase in specimen current, indicating that a non-visible crack has formed.

The appearance of a visible crack is also usually accompanied by a sharp current increase. Figure 7 is a photograph of a typical failed sample. The specimen in the foreground of the photo has visible rust staining and a visible crack, thus meeting the failure criteria defined above. It is common practice to continue the test for several days after a crack has been detected in order to ensure that the sample has failed in the designated manner.

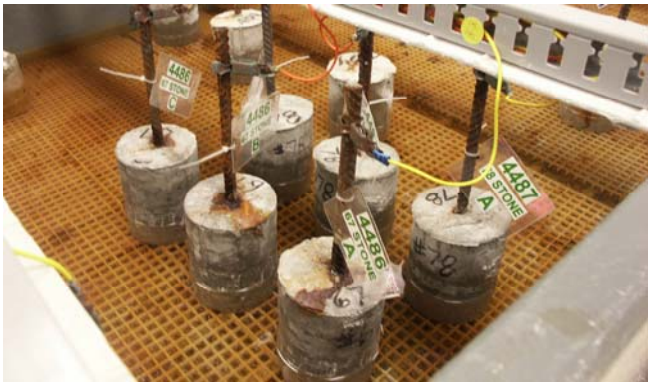

Figure 7: Photograph of impressed current apparatus and samples.

Results and Discussion

Three samples for each group (as described in Table 3) were prepared as per FM 5-522. The data in Table 3 is a summary of the results for the 12 samples tested with impressed current. Each group had three samples tested to failure. The 0.65 w/c exhibited a much earlier time to failure than the 0.45 w/c. This result is to be expected since the resistivity of concrete decreases with increasing w/c [13].

Table 3: Impressed current test results.

Specimen Group (3 Samples each)	Avg. Time to Failure (Days)	Avg. Resistance at Failure (Ω)
Control 0.65 w/c	5.7	282
Treated 0.65 w/c	13.0	414
Control 0.45 w/c	22.3	571
Treated 0.45 w/c	32.3	805

The results show that the treated samples for each group survived prolonged exposure to the corrosive environment:

- 0.65 w/c – treated samples lasted 128% longer than untreated samples
- 0.45 w/c - treated samples lasted 45% longer than untreated samples

These results indicate that the application of Surtreat TPS-II to reinforced concrete samples can have a significant effect on its durability characteristics in corrosive environments.

It is feasible to hypothesize that changes to the surface properties of the concrete were the sole contributing factor to the increase in resistivity of the concrete material. Thus, increasing the durability characteristics of the concrete material improved resistance to corrosion. However, the most interesting data trend was a significantly higher average resistance after failure was defined by the presence of a visible crack in the treated samples.

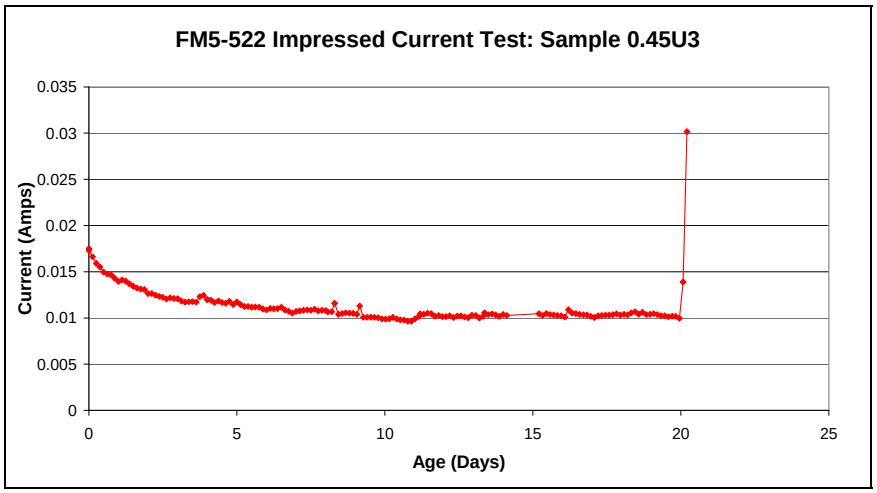

Figure 8: Impressed current data for an untreated sample.

Figure 8 depicts the plot of an untreated sample using impressed current testing and represents a typical data plot for impressed current testing. After testing begins, the current decreases over the first several days. This is followed by a period in which the current is stable with small variations. A specimen will usually maintain that current level until failure. When a crack initiates due to stresses caused by the expansion of the corrosion products, the electrolyte solution has a free path to the steel. This phenomenon results in a sudden increase in current. The current increase seen in Figure 8 typically exceeds the original current at the initiation of testing. [6]

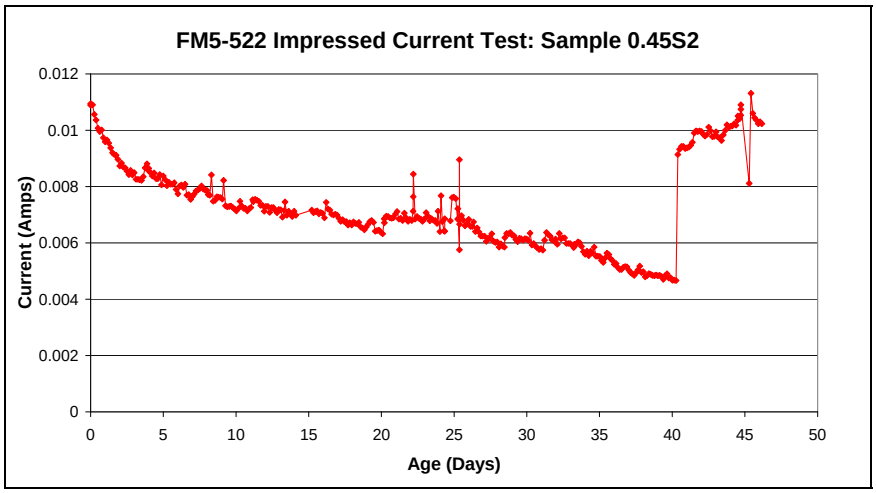

Figure 9: Impressed current data for a treated sample.

The treated samples did not behave in the same manner as the untreated samples, creating some difficulty in deciding how to describe failure for the treated samples. The current plot in Figure 9 shows that although there is a current increase at day 41, it did not exceed the initial current readings, as did like those in the control specimens (Figure 8). Since the resistance of the steel (as shown in Table 3) was significantly greater subsequent to testing and the current was significantly lower for the treated samples it is obvious that another phenomenon is also taking place, possibly the steel forming an improved passivation film that has higher resistance to chlorides. Further research is needed to study the exact causes of this effect.

4.4 Compressive Strength Testing

The compressive strength of concrete is its primary physical property due to its exclusive use in the design of reinforced structures. Compressive strength is often used as an indication of other strength properties of concrete such as flexural strength, tensile strength, torsional strength, and shear strength [15]. Compressive strength testing is one of the oldest methods of standardized testing for use in concrete materials. Testing of the compressive strength of concrete cylinders was standardized by ASTM in 1921 [7]. Traditionally, compressive strength testing has been the most widely used method of test for quality assurance in concrete materials.

Sample preparation

The sample preparation and curing regimen for these specimens was performed as per the relevant standard (ASTM C 39) [7]. Upon completion of curing at 28 days the treated samples were air cured for an additional 7 days prior to the application of Surtreat TPS-II. Following treatment, the samples were stored in air for an additional 6 days before returning to moist cure 24 hours prior to testing. The samples in the untreated group were at all times stored adjacent to the treated group, under the same conditions, prior to testing. Therefore the only difference in the conditioning of samples between the Surtreat and control groups is that the experimental group was treated with Surtreat 7 days after removal from moist curing. All of the samples for this were tested 42 days after casting.

Figure 10: Photograph of compressive strength testing

For the compressive strength testing regimen, an additional w/c (0.70) was added to the testing matrix as shown in Table 4. One reason for adding the 0.70 w/c mixture to the testing matrix was an effort to further study the effects of Surtreat TPS-II on poor quality concrete.

Results and Discussion

Table 4 provides a summary of the compressive strength data. A total of 18 cylinders were tested, 9 of which were treated and 9 of which were control specimens. The third column is a calculation of the average compressive strength increase between the control and treated specimens.

Table 4: Summary of Compressive Strength Test Results

Specimen Group (3 Samples each)	Average Ultimate Strength (psi)	% Strength Increase
Control 0.70 w/c	4763	-
Treated 0.70 w/c	5386	13.10
Control 0.65 w/c	4887	-
Treated 0.65 w/c	5255	7.54
Control 0.45 w/c	6886	-
Treated 0.45 w/c	7630	10.80

The results show that each of the sample groups exhibited increased strength following treatment with Surtreat TPS-II, though that strength increase was relatively minor. The reason for this is most likely due to the high-quality treatment of the cylinder samples after casting. It is standard practice to cure the cylinders at 100% RH for 28 days following demolding. Such practice ensures a higher degree of cement hydration than typically achieved in the field. It is generally accepted that the batching, placing and curing practices followed in the field are rarely comparable to those in the lab. To assume that concrete is cured in the field to the extent that it is under lab conditions is erroneous. Therefore, the general quality of laboratory concrete is superior to the quality of *in-situ* concrete [16].

The compressive strength values for the concrete samples used in this testing are relatively high for their respective water to cement ratios. The measured strengths for each of the control mixes shown in Table 4 are approximately 50% higher than the values which are to be expected in similar concretes placed and cured in the field [15, 17, 18]. In this specific case, the primary reason for these higher strengths is the curing regimen employed. All of the samples were moist cured by complete submersion in lime-saturated

water following demolding. Considering that the majority of the hydration reactions occur within the first 28 days [13, 15, 17, 18], it is possible to conclude that the concrete samples used for this experiment were of superior quality to that of *in-situ* concrete placed and cured the field.

Thus, it can also be concluded that the majority of the hydration reactions had taken place prior to treatment with Surtreat TPS-II. Therefore, there was most likely a lesser amount of non-hydrated cement product remaining to react with the Surtreat TPS-II and improve concrete properties than would be found in *in situ* concrete at the same age. Thus, the increase in compressive strength values seen in Table 4 could be considered a minimum when compared with the improvement of concrete in the field at the same age. Other research has verified that application of Surtreat to concrete structures cast and placed under normal field conditions has resulted in significantly higher gains [19,20].

4.5 Flexural Strength Testing

The strength of concrete for pavements and roadways is typically specified by its flexural strength [18]. This is due to the fact that flexural strength is often the controlling strength parameter in concrete pavements. The flexural strength of concrete is commonly represented by its Modulus of Rupture, as determined by ASTM C 78. For the flexural strength testing regimen, it was decided that the flexural members would be cut from concrete slabs after treatment to simulate actual field treatment and loading conditions. Following saw cutting, the resulting beam samples were tested in third-point loading as specified in ASTM C 78-02. Figures 11 and 12 contain photographs of the flexural slabs prior to cutting and the test beams during strength testing, respectively.

Figure 11: Treated slab prior to cutting flexural specimens.

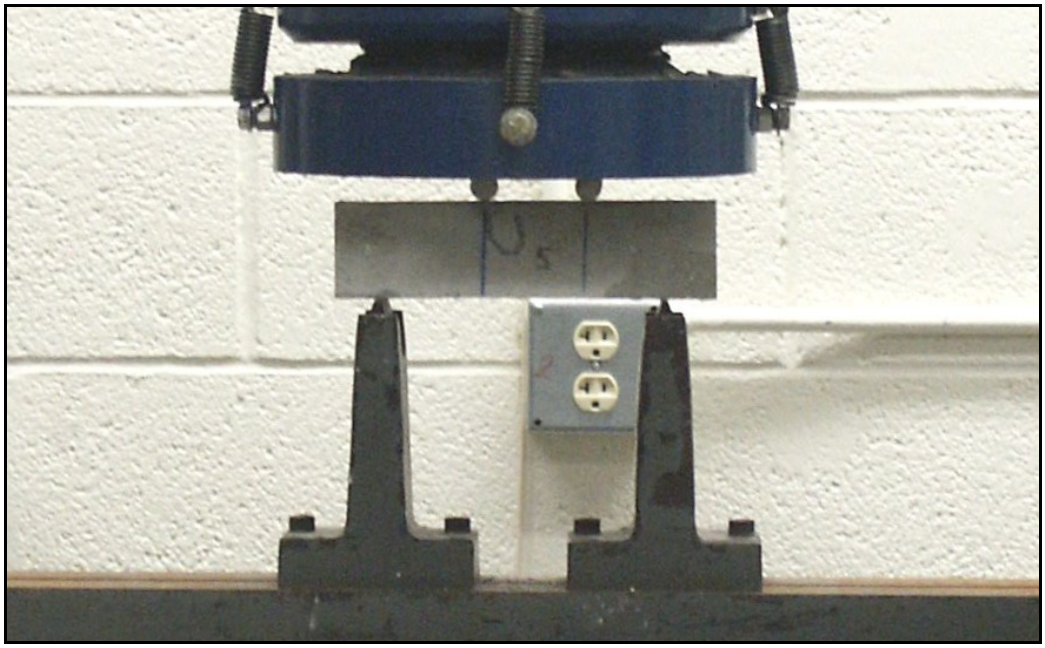

Figure 12: Flexural beam during load testing.

Results and Discussion

Table 5 is a summary of the modulus of rupture (MOR) data. A total of 40 beams were tested, 20 of which were treated and 20 of which were untreated control specimens. The third column shows the average increase in modulus of rupture between the control and treated specimens.

Table 5: Summary of Flexural Strength Test Results

Specimen Group (10 Samples each)	Average MOR (psi)	% MOR Increase
Control 0.65 w/c	740	
Treated 0.65 w/c	823	13.3
Control 0.45 w/c	1066	
Treated 0.45 w/c	1277	19.8

The values in Table 5 show an increase in modulus of rupture due to the application of Surtreat TPS-II to the concrete slab samples, indicating that the application of Surtreat to concrete can increase its modulus of rupture.

4.6 Water Absorption Testing

The majority of degradation mechanisms that affect concrete involve the penetration of aggressive materials such as sulfates, chlorides, carbon dioxide, and other deleterious agents into the concrete through its exposed surface [21]. It is often the tendency of concrete practitioners to associate the durability characteristics of concrete materials with their 'permeability'. Strictly speaking, permeability refers to the flow of fluid through a porous medium due to a pressure head. However, the movement of fluids through concrete takes place not only due to pressure induced flow, but also by diffusion, absorption, and wicking action. Thus, the true concern is with the penetrability of the concrete material [16].

Surface absorption is considered an important characteristic of concrete materials, as it measures the rate at which water is drawn into unsaturated concrete due to capillary

suction [21]. While it is not uncommon for subsurface structural elements such as foundations, piles and bridge substructures to be completely submerged and thus subjected to permeability or diffusion inducing conditions, the majority of damage actually occurs in areas of partial or cyclic exposure to liquids. This typically refers to the tidal and splash zones on bridges exposed to seawater or bridge decks in cold climates where deicing salts are prevalent. In such cases, the surface absorption of concrete can be the governing fluid transport mechanism.

The Initial Surface Absorption Test (ISAT) is used to measure the rate at which water is absorbed into concrete. There are several variations in the equipment used to obtain surface absorption values, with the Figg test commonly used to evaluate the absorption properties of concrete. The original version of the Figg test requires a small hole to be drilled into the concrete surface, after which the hole is capped by a silicone stopper. A hypodermic needle, which is connected by a series of capillaries to a syringe, is then inserted through the stopper. A water head is applied and the time required for 1 mm^3 of water to be absorbed into the concrete is recorded. The resulting value is called the absorption index and corresponds to the quality of the concrete. Figure 13 shows a schematic diagram of the original test configuration. Several modifications of the Figg test have been instituted since its original development. [16,21]

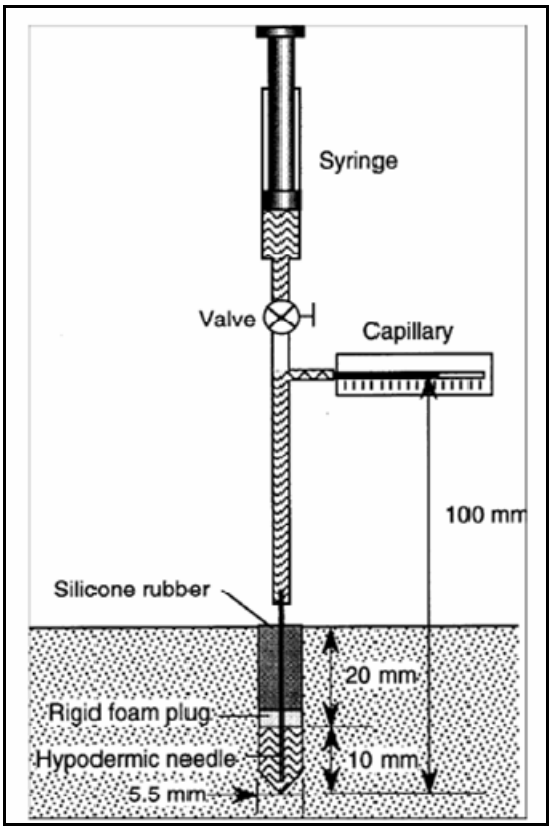

Figure 13: Schematic of the original Figg test configuration. [21]

The most recent version of the Figg test incorporates a sealed cap mounted on the surface of a concrete specimen, replacing the need for drilling a hole into the concrete structure. Figure 14 is a photograph of the typical test configuration of the Figg apparatus used in this testing program.

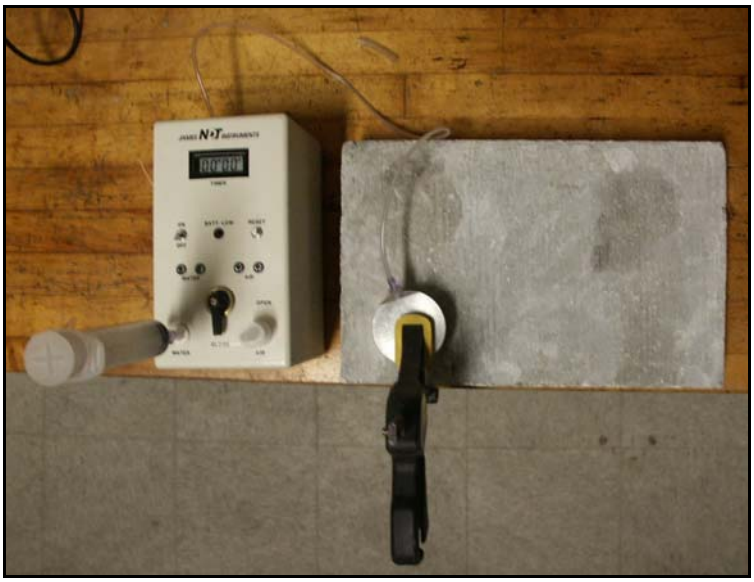

Figure 14: Figg testing apparatus used in testing program.

The sealed cap now used in the Figg test, in place of the drilled hole, has garnered the favor of many researchers. Since the cap measures the absorption properties solely through the surface of the concrete rather than at the region of concrete immediately beneath the surface, it has become a valuable resource in evaluating surface treatments and differences between surface properties of concrete materials. The surface properties differ from the subsurface properties of concrete because the finishing techniques of concrete can result in significantly different surface properties [13,16,17,18]. Therefore, performing tests directly on the surface of *in-situ* concrete can result in different results when compared with the same test performed on the subsurface of *in situ* concrete [22].

Sample preparation

Sample preparation for the absorption test was performed in the exact same manner as for the specimens used in the resistance to abrasion testing regimen. The objective of the sample preparation method was to obtain a concrete specimen with surface properties which duplicate the surface properties typically found in *in situ* concrete.

The samples and curing regimen for these specimens conformed to ASTM C 418-98 [3]. A total of four 24” x 12” x 2” rectangular prisms were cast, consisting of two control specimens and two treated specimens for each water to cement ratio.

Upon completion of curing at 28 days the treated samples were air cured for an additional 7 days prior to the application of Surtreat. Following treatment, the samples were stored in air for an additional 6 days before being returned to moist curing 24 hours prior to testing. Therefore, the only difference in the conditioning of samples between the Surtreat and control groups was that the experimental group was treated 7 days after removal from moist curing. All of the samples were tested 42 days after casting.

Results and Discussion

The surface absorption testing was performed as per the equipment manufacturer's recommendations, and as prescribed in ACI 228-R98 [21]. The data was recorded in time (sec). However, since the surface cap has a diameter of known size (30mm), the time can be converted into a time of flow of 1 mm^3 into the concrete. With a known cross-sectional area, the recorded date can be used to obtain a flow rate of surface absorption where:

- Volume of water, V = $1mm^3$
- Time, T = measured time
- Rate of flow, $Q = \frac{V}{T}$
- Area, $A = \frac{\pi \cdot d^2}{4} = \frac{\pi \cdot (30mm)^2}{4} = 706.86mm^2$
- Rate of surface absorption, $R = \frac{Q}{A}$

Table 6: Summary of Surface Absorption Test Results

Specimen Group	Avg. time to V (sec)	Rate of absorption R (m/sec)
Control 0.65 w/c	268	5.28×10^{-11}
Treated 0.65 w/c	501	2.84×10^{-11}
Control 0.45 w/c	796	1.78×10^{-11}
Treated 0.45 w/c	1064	1.33×10^{-11}

The results in Table 6 show that absorption characteristics are significantly improved due to treatment with Surtreat. For the 0.65 w/c samples the decrease in absorption was 46% and for the 0.45 w/c samples the decrease was 28%.

4.7 Water Permeability Testing

Permeability testing is similar to absorption testing in that it measures the penetrability of concrete materials. The primary differences between permeability and absorption testing are; permeability testing measures the flow of water due to a pressure head and the concrete is saturated during testing. Presently, there is no standardized test for measuring the true permeability of concrete. In the late 1980's the University of Florida developed a test that measures the rate of flow through concrete using a compressed air source to drive water movement. Subsequently, the Florida Department of Transportation used this research design to create their permeability test apparatus. This test setup has been demonstrated to be both reliable and efficient in determining permeability of concrete specimens [23]. Researchers within the United States, and the international community, have since developed similar devices which use a comparable test apparatus to that developed at the University of Florida [24].

Specimen Preparation

The specimens used for the permeability test are made by cutting a 100 x 200 mm cylinder into 50 mm thick discs, after which a thin layer is removed from the specimen surface to ensure that dust and other potentially loose particles are not present on the sample. A 25 mm thick layer of epoxy is cast around the specimen to ensure that the applied water passes only through the sample and is unidirectional. Figure 15 contains a photograph and schematic of a typical device used for permeability testing [23].

The sample preparation and curing regimen for these specimens was performed as per the same methods used for that of compressive strength testing samples. [7]. Upon completion of curing at 28 days the treated samples were air cured for an additional 7 days prior to the application of Surtreat TPS-II. Following treatment, the samples were stored in air for an additional 6 days before returning to moist cure 24 hours prior to testing. Therefore, the only difference in the conditioning of samples between the Surtreat and control groups is that the experimental group was treated 7 days after removal from moist curing. All of the samples were thus tested 42 days after casting.

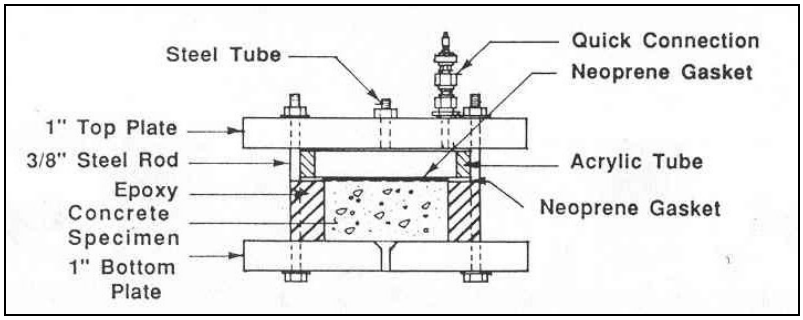

Figure 15: Water permeability test.

Testing Procedure

The permeability test specimen is placed into the testing apparatus, which is essentially a pressure chamber, with a pressurized water entry used to saturate the sample and create a manometer reading, and a pressurized air fitting that keeps the system and sample under constant pressure. The sample is connected to the permeability apparatus by a tube which runs along a calibrated measuring board (shown in Figure 16). The system was designed to be simple in nature to ensure that it could be recreated in durability testing labs throughout the world. Figure 16 is a photograph of the test configuration with 2 samples being tested. The FDOT apparatus is capable of testing 10 samples concurrently, and the permeability laboratory at the University of Florida has the ability to test 20 samples concurrently.

Figure 16: Permeability test apparatus.

After the specimens are epoxy-coated and the epoxy cured, permeability testing can begin. The testing regimen is initiated by attaching the saturated samples to the pressurized air system and keeping a periodic record of the water levels in the manometer tubes. Readings are taken until the system reaches a constant flow rate (i.e. constant change in water level). Upon the establishment of a constant flow rate, the coefficient of permeability can be calculated from the flow rate.

Results and Discussion

The coefficient of permeability of a concrete test specimen is calculated from the net rate of flow, based on Darcy's Law. The original equation has been modified slightly to calculate the permeability coefficient of pressurized test samples:

$$K = \rho \frac{H \cdot Q}{P \cdot A}$$

Where:

- K = the coefficient of permeability (m/sec)
- ρ = the density of water (kg/m^3)
- H= the length of the test specimen (mm)
- P = water pressure (psi) or (kg/cm^2)
- Q = the net rate of inflow (cm^3/sec)
- A = cross-sectional area of test specimen (mm^2)

Table 7: Summary of Permeability Test Results

Specimen Group	Coeff. of Permeability, K (m/sec)
Control 0.65 w/c	4.39×10^{-19}
Treated 0.65 w/c	2.74×10^{-19}
Control 0.45 w/c	1.78×10^{-19}
Treated 0.45 w/c	8.01×10^{-20}

The results in Table 7 show that the permeability characteristics were improved by application of Surtreat. For the 0.65 w/c samples, the decrease in permeability was 38% and for the 0.45 w/c samples the decrease was 27%.

4.8 Microscopic Evaluation

The scanning electron microscope is used extensively in materials science and has many applications in hardened concrete investigation [25]. For this research, a Hitachi Model S-3000N Variable Pressure Scanning Electron Microscope (SEM) equipped with and Energy Dispersive X-Ray Spectrometer (EDS) was used. The EDS was employed to determine elemental composition of the hardened cement paste for both treated and control samples. Due to the origin (laboratory conditioning) of the samples, it was not necessary to evaluate the concrete for distress or defects.

Results and Discussion

The values obtained by the EDS from a control sample and a treated sample are plotted in Figures 17 and 18, respectively. The microscopic analysis was performed exclusively on the hardened cement paste portion of the concrete. The numerical summaries, showing weight percent and the atomic percent of each element are provided in Tables 8 and 9. Samples for the EDS were taken at depths of 12.5 mm below the surface of the concrete for both the treated and control samples. As stated previously, it is generally accepted that the quality of laboratory cured concrete is typically superior to the quality concrete *in situ* concrete. [16] Thus, due to the relatively good quality of the specimens tested herein, it is likely that greater penetration depths would be achieved in field placed concrete, especially concrete that has experienced cracking and deterioration.

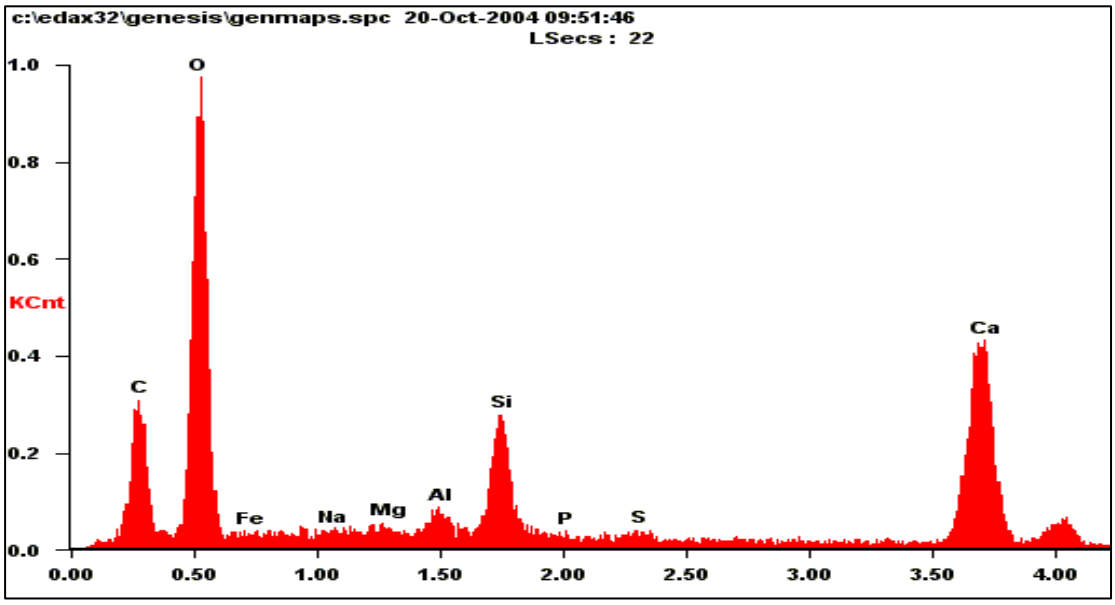

Figure 17: EDS Spectrum - Control Sample

Table 8: Summary of EDS Spectrum - Control Sample

Element	***Wt%***	***At%***
O	**40.88**	**62.29**
Fe	1.81	0.79
Na	0.42	0.45
Mg	0.76	0.76
Al	1.20	1.08
Si	**4.21**	**3.66**
P	0.27	0.21
S	0.50	0.38
Ca	**49.94**	**30.37**

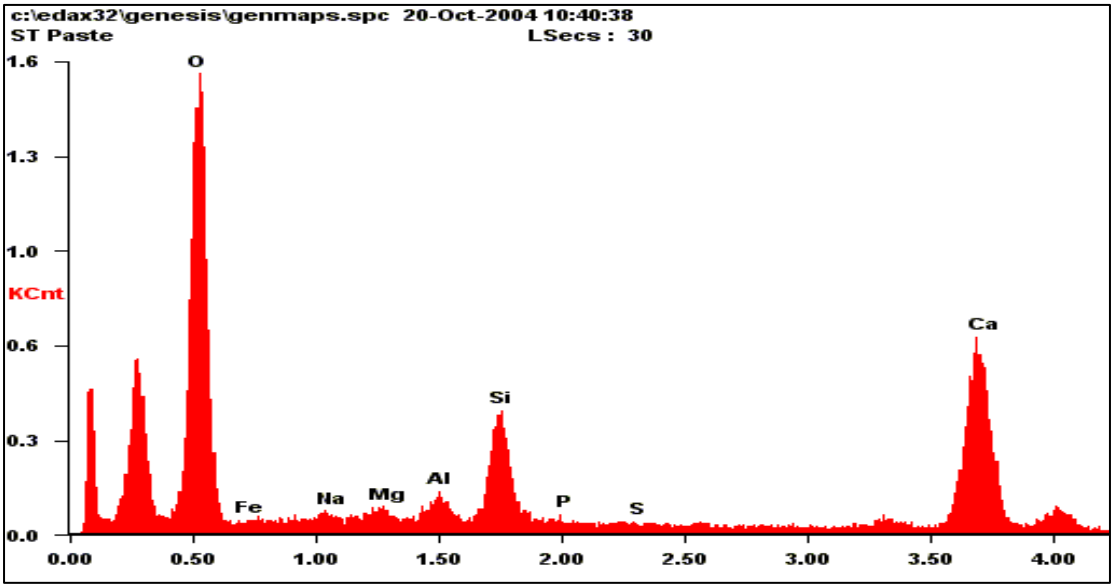

Figure 18: EDS Spectrum - Treated Sample

Table 9: Summary of EDS Spectrum - Treated Sample

Element	***Wt%***	***At%***
O	**46.23**	**66.60**
Fe	2.09	0.86
Na	0.41	0.41
Mg	0.67	0.64
Al	1.42	1.42
Si	**7.24**	**5.94**
P	0.27	0.21
S	0.74	0.53
Ca	**40.70**	**23.40**

The elemental analysis of the concrete samples revealed that the chemical composition of the hardened cement paste was altered by the application of Surtreat TPS-II. The proportions of Oxygen and Silicon increased, though it was likely the addition of Silicon that is the most probable reason for the improved physical characteristics of the hardened concrete subsequent to treatment.

5 Conclusions

The physical results obtained from the testing regimen indicated that concrete samples topically treated with Surtreat TPS-II showed improvement in each of the tests conducted, implying that the treatment of concrete with Surtreat TPS-II can result in improvements to:

- the scaling resistance of concrete surfaces exposed to deicing chemicals,
- the abrasion resistance of concrete to sandblasting,
- the protection of steel embedded within concrete from corrosion,
- the compressive strength of concrete,
- the flexural behavior of concrete,
- the penetrability characteristics of concrete, through reduction in the water absorption and water permeability properties.

The use of Surtreat TPS-II appears to be a viable option for rehabilitation of existing concrete structures through its ability to improve the durability characteristics of the concrete itself.

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7 Appendix A

ASTM C 642 98 Salt Scaling Data
Cumulative Mass Loss sample set for w/c = 0.65

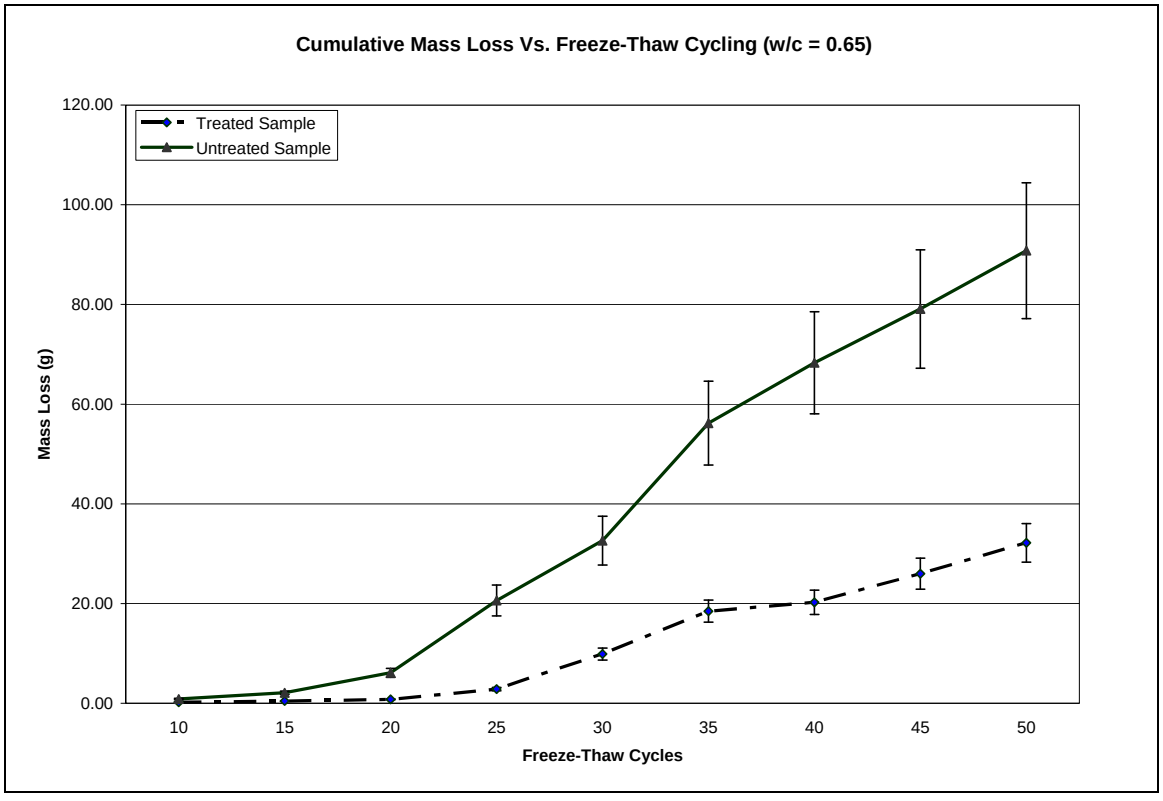
Name of sample	Mass loss 10 cycles tare wt (g)	Mass loss 15 cycles tare wt (g)	Mass loss 20 cycles tare wt (g)	Mass loss 25 cycles tare wt (g)	Mass loss 30 cycles tare wt (g)	Mass loss 35 cycles tare wt (g)	Mass loss 40 cycles tare wt (g)	Mass loss 45 cycles tare wt (g)	Mass loss 50 cycles tare wt (g)
S-1	0.00	0.00	0.00	2.65	7.40	15.91	17.44	22.48	28.01
S-2	0.63	1.31	2.30	3.20	11.25	22.00	23.71	29.74	35.91
S-3	0.00	0.00	0.00	2.65	10.94	17.51	19.58	25.79	32.59
U-1	0.63	1.41	3.75	6.72	11.48	24.80	34.01	45.84	57.99
U-2	0.78	1.92	8.81	26.09	40.80	69.74	83.60	93.48	104.82
U-3	1.08	2.97	5.76	29.07	45.59	74.03	87.35	97.95	109.56

St Dev S	0.36	0.75	1.33	0.31	2.14	3.16	3.19	3.64	3.96
AvgS	0.21	0.44	0.77	2.83	9.86	18.47	20.24	26.00	32.17

COV S **0.123**

St Dev U	0.36	0.79	1.89	2.21	0.27	3.68	7.43	10.62	13.81
AvgU	0.83	2.10	6.11	20.63	32.62	56.19	68.32	79.09	90.79

COV U **0.152**

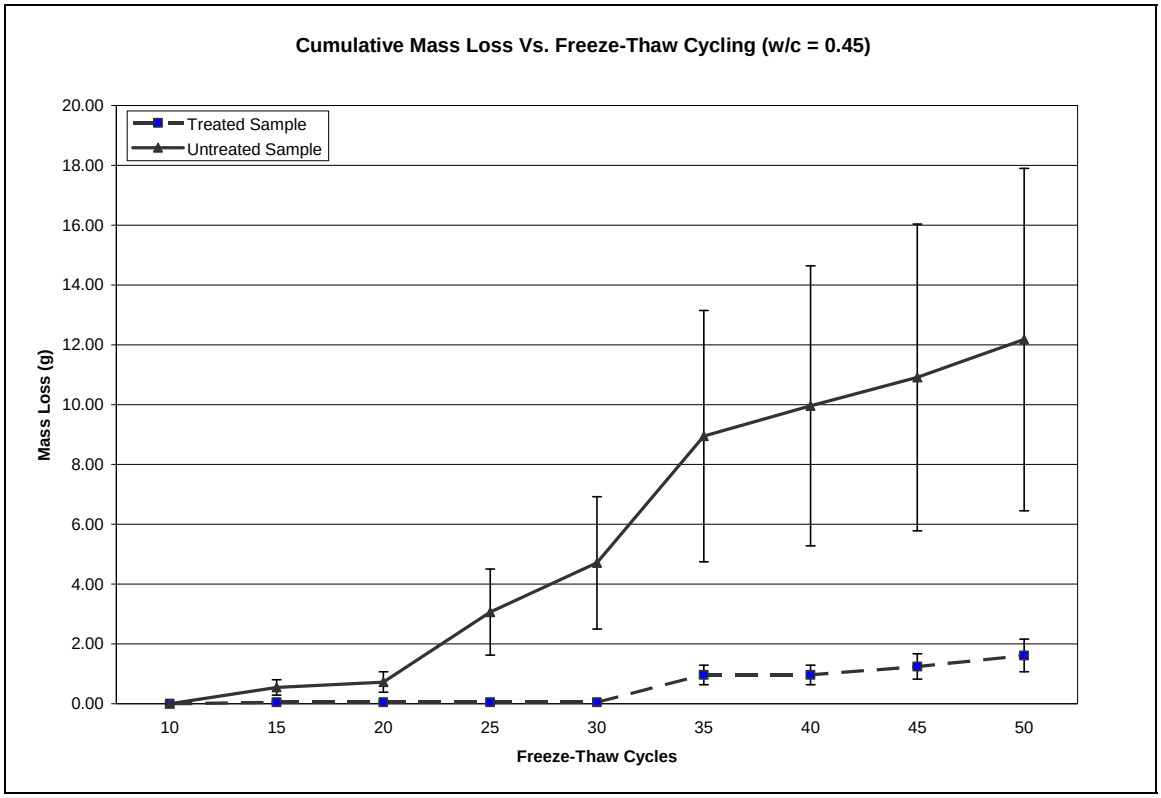


ASTM C 642 98 Salt Scaling Data
Cumulative Mass Loss sample set for w/c = 0.45

Name of sample	Mass loss 10 cycles tare wt (g)	Mass loss 15 cycles tare wt (g)	Mass loss 20 cycles tare wt (g)	Mass loss 25 cycles tare wt (g)	Mass loss 30 cycles tare wt (g)	Mass loss 35 cycles tare wt (g)	Mass loss 40 cycles tare wt (g)	Mass loss 45 cycles tare wt (g)	Mass loss 50 cycles tare wt (g)
S-1	0	0	0	0	0	0.89	0.89	1.01	1.24
S-2	0	0.15	0.15	0.15	0.15	1.54	1.54	1.88	2.25
S-3	0	0	0	0	0	0.46	0.46	0.84	1.35
U-1	0	0.22	0.22	0.22	0.22	2.18	2.18	3.81	5.51
U-2	0	0.46	0.99	3.83	6.1	11.53	13.61	14.14	15.66
U-3	0	0.96	0.96	5.14	7.81	13.13	14.09	14.78	15.36

St Dev S	0	0.09	0.09	0.09	0.09	0.54	0.54	0.56	0.55
AvgS	0	0.05	0.05	0.05	0.05	0.96	0.96	1.24	1.61
COV S	**0.343**								

St Dev U	0	0.38	0.44	2.55	3.98	5.91	6.74	6.16	5.78
AvgU	0	0.55	0.72	3.06	4.71	8.95	9.96	10.91	12.18
COV U	**0.474**								



Data and Calculations for Absorption Testing

Control w/c = 0.65
All data in time (sec)

Location	Volume (m^3)	Time (sec)	$Q = m^3/s$	Area (m^2)	Rate of Absorption (m/sec)
1	1E-11	260	3.851E-14	7.069.E-04	5.45E-11
2	1E-11	268	3.731E-14	7.069.E-04	5.28E-11
3	1E-11	276	3.623E-14	7.069.E-04	5.13E-11

Treated w/c = 0.65
All data in time (sec)

Location	Volume (m^3)	Time (sec)	$Q = m^3/s$	Area (m^2)	Rate of Absorption (m/sec)
1	1E-11	455	2.198E-14	7.069.E-04	3.11E-11
2	1E-11	507	1.972E-14	7.069.E-04	2.79E-11
3	1E-11	541	1.847E-14	7.069.E-04	2.61E-11

Control w/c = 0.45
All data in time (sec)

Location	Volume (m^3)	Time (sec)	$Q = m^3/s$	Area (m^2)	Rate of Absorption (m/sec)
1	1E-11	260	3.851E-14	7.069.E-04	5.45E-11
2	1E-11	268	3.731E-14	7.069.E-04	5.28E-11
3	1E-11	276	3.623E-14	7.069.E-04	5.13E-11

Treated w/c = 0.45
All data in time (sec)

Location	Volume (m^3)	Time (sec)	$Q = m^3/s$	Area (m^2)	Rate of Absorption (m/sec)
1	1E-11	455	2.198E-14	7.069.E-04	3.11E-11
2	1E-11	507	1.972E-14	7.069.E-04	2.79E-11
3	1E-11	541	1.847E-14	7.069.E-04	2.61E-11

Compressive Strength Data (ASTM C39)

Sample Name	Ult Load (lb)	Ult Strength (Psi)	Avg Ult Str	% Increase C - T
U1 70	63417	5047		
U2 70	62607	4982	5141	**4.76**
U3 70	67790	5395		
S1 70	70181	5585		
S2 70	65850	5240	5386	
S3 70	67000	5332		
U1 65	62220	4951		
U2 65	62016	4935	4968	**3.13**
U3 65	63040	5017		
S1 65	65367	5202		
S2 65	63507	5054	5123	
S3 65	64265	5114		
U1 45	80795	6430		
U2 45	85112	6773	6886	**10.80**
U3 45	93680	7455		
S1 45	99863	7947		
S2 45	101421	8071	7630	
S3 45	86341	6871		

Impressed Current Data (FM 5-522)

Sample Name	Time to Failure (days)	Resistance (ohms)	Avg Time to Failure (days)	Avg Resistance (ohms)
65 S1 - Sample A	8	398		
65 S2 - Sample B	14	434	13.00	413.67
65 S3 - Sample C	17	409		
65 C1 - Sample A	10	312		
65 C2 - Sample B	2	255	5.67	282.00
65 C3 - Sample C	5	279		
45 S1 - Sample A	17	536		
45 S2 - Sample B	40	902	32.33	804.67
45 S3 - Sample C	40	976		
45 U1 - Sample A	27	661		
45 U2 - Sample B	20	467	22.33	570.67
45 U3 - Sample C	20	584		

Flexural Strength data and Calculations (ASTM C78)

Treated w/c 0.45

Sample #	Ultimate Load (lb)	Flexural Strength (psi)
S-1	1765	1323.8
S-2	1885	1413.8
S-3	1845	1383.8
S-4	1965	1473.8
S-5	2120	1590.0
S-6	1791	1343.3
S-7	1537	1152.8
S-8	1357	1017.8
S-9	1383	1037.3
S-10	1383	1037.3
Avg Mod of Rupture (psi)		**1277.3**
Standard Deviation (psi)		**203.0**
COV %		**15.9%**

Control w/c 0.45

Sample #	Ultimate Load (lb)	Flexural Strength (psi)
U-1	1363	1022.3
U-2	1591	1193.3
U-3	1530	1147.5
U-4	1470	1102.5
U-5	1223	917.3
U-6	1537	1152.8
U-7	1343	1007.3
U-8	1277	957.8
U-9	1310	982.5
U-10	1571	1178.3
Avg Mod of Rupture (psi)		**1066.1**
Standard Deviation (psi)		**100.3**
COV %		**9.4%**

Treated w/c 0.65

Sample #	Ultimate Load (lb)	Flexural Strength (psi)
S-1	1000	750.0
S-2	1056	792.0
S-3	1156	867.0
S-4	1163	872.3
S-5	1069	801.8
S-6	1103	827.3
S-7	1023	767.3
S-8	1096	822.0
S-9	1196	897.0
S-10	1123	842.3
Avg Mod of Rupture (psi)		**823.9**
Standard Deviation (psi)		**47.2**
COV %		**5.7%**

Control w/c 0.65

Sample #	Ultimate Load (lb)	Flexural Strength (psi)
U-1	902	676.5
U-2	992	744.0
U-3	962	721.5
U-4	976	732.0
U-5	962	721.5
U-6	1076	807.0
U-7	1029	771.8
U-8	1136	852.0
U-9	949	711.8
U-10	883	662.3
Avg Mod of Rupture (psi)		**740.0**
Standard Deviation (psi)		**57.4**
COV %		**7.8%**