

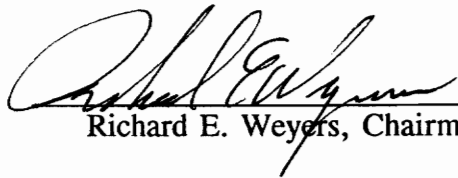
**Determination of the Service Life of Concrete
Sealers on Horizontal and Vertical Bridge Members**

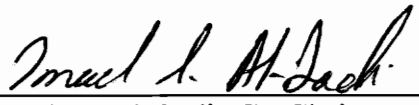
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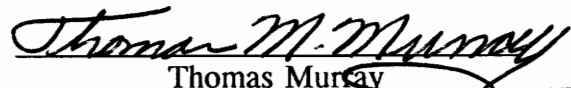
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Thesis submitted to the Faculty of the
Virginia Polytechnic Institute and State University
in partial fulfillment of the requirements for the degree of
Master of Science
in
Civil Engineering

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January 18, 1992

Blacksburg, Virginia

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**Determination of the Service Life of Concrete
Sealers on Horizontal and Vertical Bridge Members**

by

Rick O. Drumm

Committee chairman: Richard E. Weyers

Civil Engineering

(ABSTRACT)

Due to the increasing rate of deterioration of concrete bridges caused by exposure to chlorides, it has become apparent that effective protection methods need to be employed which will prevent chlorides from reaching critical contamination within the life of the structure. One method of protection is the application of concrete surface sealers which form water-resistant barriers and reduce chloride intrusion. It is imperative to know how effective sealers are and how long sealers retain their effectiveness in order to plan reapplication and estimate life cycle costs for comparison to other maintenance activities. This research was conducted to predict the service life of concrete sealers for both horizontal and vertical bridge components. As a secondary goal, the use of a rapid, non-destructive Surface Absorption Test (SAT) was investigated as a possible substitute for analyzing the condition of sealers. This was done by comparing SAT results with the standard concrete sampling and chloride analysis technique typically employed.

Four sealers were applied to horizontal laboratory specimens (slabs), vertical laboratory specimens (wall sections), and bridges (high-volume and moderate-volume). Control sections were also included in all specimen types. The laboratory specimens were exposed to a 3% NaCl solution for 30 1-week cycles, each cycle being three days of exposure and four days of air drying.

Background chlorides and the chloride ion profiles were determined after 10, 20 and 30 cycles of salt water exposure. The surface absorption test was conducted at various intervals throughout the cycles. The surface absorption test was also used to attempt to measure the traffic wear effect on the field specimens.

The results indicate that the two epoxies exhibited very little effectiveness in preventing chlorides from entering the concrete. The silane and siloxane sealers performed much better in the laboratory settings, retaining over 90% reduction of chlorides throughout the test period. A service life model which includes laboratory performance and considers application exposure conditions is suggested.

It has been discovered that, at present, surface absorption testing may be used on a limited basis to obtain results which indicate sealer effectiveness, but only if the testing occurs under extremely limited or controlled environments.

ACKNOWLEDGEMENTS

The author wishes to thank the one person without whom all this research would not have been possible, the one whose knowledge of concrete and concrete sealers is far beyond anything I can imagine, the one who was faithful to me through all of my weaknesses and failures, the one who has given me the understanding of this subject matter - Jesus Christ.

Gratitude is also expressed to Dr. Richard E. Weyers who gave me the opportunity to learn about concrete, sealers, research, and university life. His help in my educational advancement is duly noted. Also, thanks are deserved for Imad Al-Qadi for his help in this endeavor, and Thomas Murray for his cooperation.

The author also expresses appreciation for the fellow members of the Materials Lab, most notably Brian Prowell and Eric Peterson who located countless tools and shared techniques used in the lab. Also acknowledged is the guidance and support given by Mike Fitch, Marcia Prowell, Erin Larsen, Holly Ratcliff, and Jerzy (Jurek) Zemajtis. A great deal of much appreciated help was also received from Dennis Huffman and Brett Farmer, without which, much of the hands-on work would hardly have been learned or accomplished.

Of all human help received, none has been greater than that received from Susan - my editor, my friend, my greatest encourager, and my wife. Also, for his unknowing patience, I wish to show appreciation for my son, Eli. Susan and Eli are gifts from God.

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1.0.

INTRODUCTION

1.1. Description of the Problem

Our nation's bridges are in need of much attention. Of the more than 577,000 bridges in the United States, 41% have been found to be functionally obsolete or deficient. In order to keep pace with bridge repair and replacement, \$4.2 billion would need to be spent annually, and with the backlog presently growing, this number will undoubtedly increase [1]. Therefore, there is a great need to protect present structures and ones being built from the same deterioration processes which have caused premature failure of various bridge components.

One of the major factors which adversely affects the durability of concrete bridges is corrosion of the reinforcing bars. The oxidation of the normally passive rebars may be caused by a variety of situations, but most notably, the ingress of chlorides from deicing salts in the north or seawater along the coast. Chlorides are the most prevalent substance which affects the integrity of concrete decks [2]. Chloride diffusion is responsible for a great amount of the degradation of concrete bridge deck riding surfaces, and, recently, has been noticed to contribute to

substructure deterioration as well.

As shown in Figure 1.1, in a model of concrete bridge deck deterioration due to chlorides, it can be noted that three separate time zones occur before rehabilitation is necessary. First, there is a period of chloride diffusion when the chlorides applied to the surface begin to penetrate into the concrete and chloride concentrations at the rebar level rise [3]. At the point of critical chloride contamination at rebar level, generally agreed to be between 1.0 and 2.0 lb/yd³, the corrosion process is initiated [4]. This time period continues until damage in the form of delaminations, spalls, cracks, begins to form [3]. This damage is due to the oxidized metal occupying up to 20 times the volume of the original metal [5]. This damage continues to grow, occupying greater portions of the bridge deck until, at some point, rehabilitation is needed.

In order to ensure that rehabilitation would not be needed in the lifetime of the bridge, generally taken as 50 years, one approach is to prevent the chlorides from diffusing to the rebar and reaching the critical levels. There are various methods used to prevent or curtail chloride ingress. Among the methods employed are using dense concrete, greater cover depth, waterproofing membranes, and sealers. It is this last approach on which this research focuses.

As for the two types of protective materials used on concrete surfaces, membranes are impenetrable coatings whereas sealers are solutions or suspensions in solvents which reduce water intake. Sealers are much less expensive, do not make

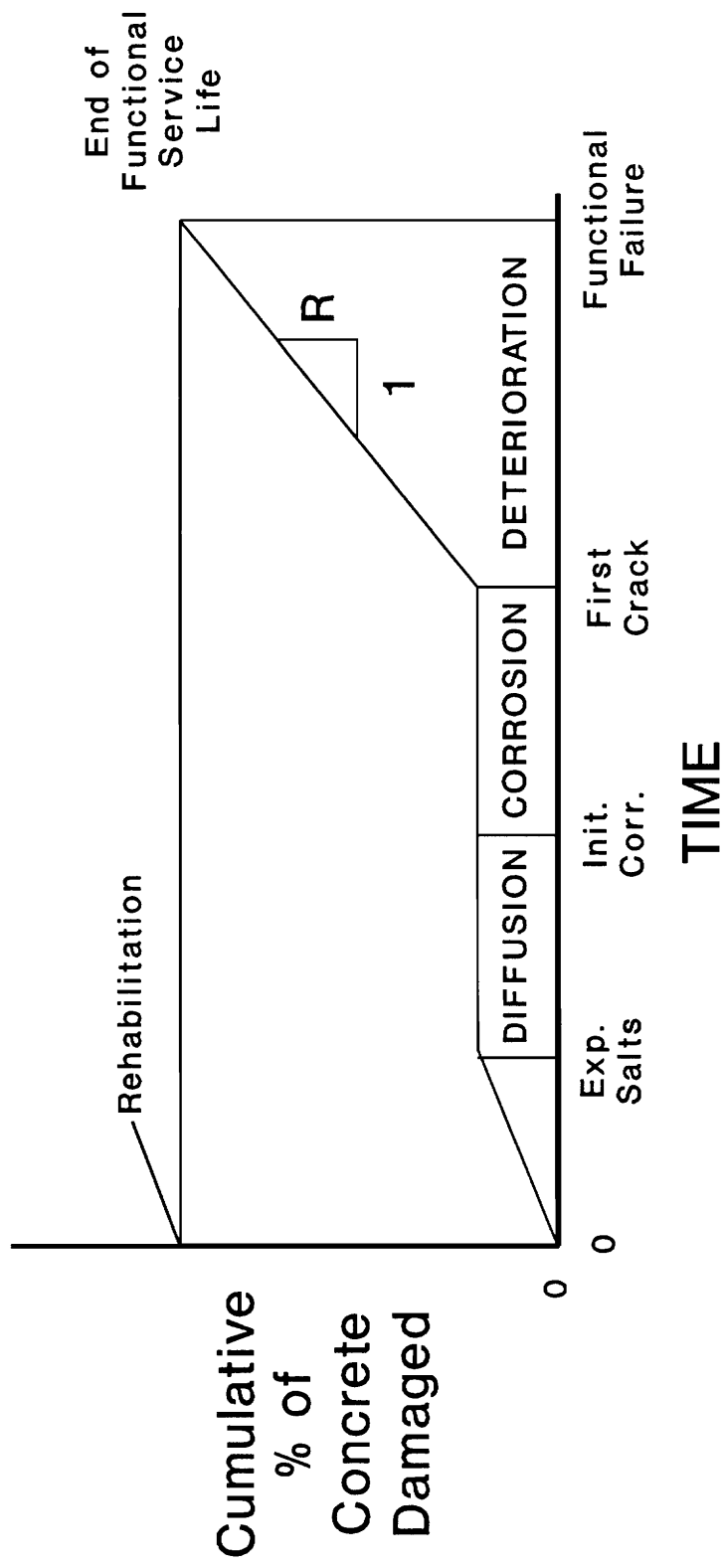


Figure 1.1 Deterioration Model for Bridge Decks [3]

concrete repair necessary, and do not hamper visual concrete inspection [6].

As in the case of any structural or mechanical device, it is most probable that preventive maintenance can be extremely cost effective in the long run [7]. Although activities such as ensuring proper drainage and spring washings are preventive maintenance, their goal is only to reduce the amount of time concrete is exposed to chlorides. As discussed later, of the methods available to prevent chloride ingress or repair contaminated concrete, the use of sealers is by far the least expensive [7]. The question remains: since sealers need to be reapplied periodically, are they feasible and economical at their present service life? To answer this question, the service life of the sealer needs to be known.

Sealers have been used on a variety of structures, most notably parking garages [8] and bridges [7]. In fact, of the 61 United States and Canadian highway agencies, only six have never used or experimented with sealers [9]. No universal standard exists to evaluate sealers, and comprehensive data on sealer performance and durability has been variable and is difficult to attain and interpret [8]. Environmental effects which vary from site to site, namely ultraviolet light and abrasion when exposed to traffic, play important roles in determining the service life of sealers [2].

Proponents of sealer use do not view sealers as a universal solution to corrosion problems. Indeed, even if sealers prove to be a fruitful method of protecting concrete, it is important to remember that many protection schemes such as admixtures, epoxy-coated rebars, surface coatings, and alternative cements, should

play a role in infrastructure protection [10]. Sealer application is no substitute for using good quality dense concrete [6]. Also, "the use of properly consolidated and properly cured low water-to-cement ratio concrete and deep cover over the embedded reinforcing steel is still needed for long-term protection in severe environments" [11].

1.2. Scope of the Study

The main goal of this research is to determine the service life of the concrete sealers tested. These estimations are only applicable to the sealers used, but the process by which this is accomplished could be used to test other sealers as well.

Three specimen types were utilized in order to achieve this goal. Horizontal surfaces, vertical surfaces, and bridge decks in the field were used. With a control section in each specimen type, four sealers were chosen and tested. The laboratory specimens were exposed to salt through ponding for the slabs and continuous salt water wetting for the wall, while the field specimens were exposed to the normal conditions in the field which were not simulated in the lab, most notably, exposure to abrasion from traffic.

The primary method of measuring the effectiveness of the sealers in the laboratory specimens was chloride content measurement at various depths. Background chloride contents and three measurement intervals spaced throughout the 30-week ponding schedule were performed.

The secondary goal of this research was to explore the feasibility of using a Surface Absorption Test (SAT) as a rapid, nondestructive method of determining the performance of sealers in-situ. The device and procedure used to measure the surface absorption of the sealed and unsealed concrete specimens was developed by Construction Technology Laboratories for SHRP Project C-101, Task C-2 [12]. SAT measurements were taken before ponding and at various intervals during the cycles. These absorption tests were also used to attempt to quantify the field test sections.

2.0.

BACKGROUND

2.1. Sealer Types

There are a wide variety and large number of concrete sealers on the market today, with more being developed all the time. Sealers vary in both chemical composition and in method of performance.

Sealers can be classified as penetrants or coatings. Quoting a work by the Ontario Ministry of Transportation, Bickley and Liscio stated that the criteria separating the two is that a coating penetrates less than 0.08 in. (2 mm), and penetrants have a greater than 0.08 in. (2 mm) penetration [8]. Coatings are often stated as being penetrating sealers, but actually do not penetrate and should be called coatings [13]. Only 35% of sealers tested recently actually penetrated to any appreciable depth. The rest should be classified as coatings [6].

A large number of generic types of sealers exists with numerous brand names for each generic type. These categories include acrylics, siloxanes, epoxies, blends of different sealer types, urethanes, silanes, silicates/siliconates, polysiloxanes/silicones, styrene-acrylate copolymers, chlorinated rubbers, oils, and synergistic systems

utilizing more than one of the above [6]. Only three generic types could be considered penetrating sealers: boiled linseed oil, silanes, and siloxanes [14].

There does seem to be general trends of performance associated with generic types of sealers [6], but results of tests show high variability within generic types. Among the best performers are epoxies, urethanes, latexes, silanes, and silane-siloxanes blends [14].

2.1.1.1. Coatings

Many sealer manufacturers claim that their product is a penetrant, but, as mentioned, very few generic types could truly be considered anything but a coating. These include epoxies and a variety of other sealers.

2.1.1.1.1. Epoxies

Epoxies have been applied to concretes for approximately 35 years. They consist of an epoxy resin and a hardener which must be mixed together immediately before application. The two components react with one another and form a thermosetting solid compound. They usually must be applied at temperatures above 40°F (5°C). Epoxies are extremely varied in formulation and performance [15].

In 1979, epoxies were found to be the second most common type of sealer used, and presently, they are being applied to a great extent. Epoxies typically have solid contents between 17 and 100%. A general trend of decreasing resistance to

chloride intrusion with decreasing solids content was noted during past testing. The high solids epoxies had a glossy appearance. This would make them unsuitable for any wearing surface since this appearance would be dangerous to drivers. Water-based epoxies have recently been developed to meet environmental specifications, and epoxies and urethanes applied over a silane primer have also been used in experiments [14].

Epoxies have proven to be quite inconsistent in terms of test results. Many tests show extremely favorable results, while others rank epoxies poorly. This may well be due to variations in the specific formula, varying ambient conditions, or different surface preparation techniques [15].

2.1.1.2. Others

A wide range of generic products have been experimented with and used for concrete protection. Among the other categories discussed in specific are acrylics, polyurethanes, and hydrocarbon resins. For the most part, these chemicals enter the concrete as monomers and polymerize within the pore structure of the concrete. This action essentially blocks the pores, but since very little penetration actually occurs, these sealers are still considered coatings (though some attempt to classify some of them as penetrants). Acrylic resins with methylmethacrylate have received high marks in many tests [15]. Also, an acrylic topcoat over a silane primer has been highly rated [13]. Polyurethanes are packaged in a wide variety of methods, a few of

which have been somewhat successful in testing, but some also performed rather poorly [15]. Urethanes and latexes vary in color [14]. Latex coatings helped prevent salt scaling but are usually rated poorly in preventing salt intrusion. There are numerous other types not mentioned here, but also which have highly contrasting formulations and performances in tests [15].

2.1.2. Penetrants

The investigation and use of penetrating sealers is becoming more prevalent due, in part, to the interest in more durable sealers, particularly for protecting bridge decks. Decks present most of the problems in sealer durability due to their greater exposure to salt, abrasion, and ultraviolet rays [7]. It is believed that since the sealer penetrants into the concrete, it will be protected against the effects of traffic wear and ultraviolet light exposure.

Sealers may also be divided into two major groups: 1) pore blockers which plug the pores in order to prevent water absorption, and 2) hydrophobic penetrates which react chemically with the hydrated cement products and form a hydrophobic layer on the pore wall [16]. Although all coatings could be considered pore blockers, only one of the common penetrants, namely linseed oil, is truly a pore blocker. The silicon-based silane and siloxane groups are categorized as hydrophobic penetrants.

2.1.2.1. Linseed oil

Linseed oil is a product obtained from flax seeds. It is a yellowish drying oil which is one of the oldest materials used to protect concrete from water intrusion [17].

In 1979, boiled linseed oil was found to be the most common type of sealer used [14]. In a recent survey of states and Canadian provinces, it was noted that linseed oil, the sealer of choice in the past, has greatly decreased in use due to its need for frequent reapplication, relative ineffectiveness, and surface discoloration. Even with reduced popularity, it is still commonly used today [9]. A typical estimate of the time needed before reapplication is necessary would be 3 years [17], but agencies often use more frequent intervals.

Linseed oil films are highly questionable when long-term effectiveness is considered. They are vulnerable to lime attack from the concrete which produces a saponification, causing adhesion loss [13].

Due to its popularity in the past, a number of studies which examine the effectiveness of sealers use linseed oil treatment as the "control" [17].

2.1.2.2. Silanes and Siloxanes

The nomenclature of silicon-based weatherproofing material is fairly vague, with many suppliers not completely aware of the exact nature of the materials they produce [18].

Silanes and siloxanes are considered hydrophobic sealers since they consist of molecules which both bind to the substrate and act as hydrophobic agents, repelling water, in the pores. Silanes are relatively small molecules, while siloxanes are larger, usually containing 2 to 10 silane molecules grouped together [19].

In chemical terms, silicon compounds can be put into one of two categories - monomers or polymers. These can further be sorted according to the type of molecules attached to the silicon atom. For sealers, two groups are chemically bound to the silicon atom. The organic hydrocarbon groups (organofunctional groups) are responsible for the hydrophobicity of the sealer. The hydrolyzable groups (silicon functional groups), such as chloro or alkoxy, are responsible for the sealer's reactivity with siliceous and similar substrates. The ratio between these two groups helps determine many of the characteristics of the sealer [18].

A silicon-based sealer with four silicon functional groups and no organofunctional groups is a silicate. Silicates act strictly as pore blockers. If the molecule contains two silicon functional groups and two organofunctional groups, the sealer is a silicone. These are attracted to the substrate but do not form bonds with it [18]. Silanes, siloxanes and siliconates are all classified together since they have three silicon functional groups and an organofunctional group. They bond with each other and the substrate when applied, and the size and shape of the organofunctional group determines the degree of hydrophobicity. For alkyl alkoxy silanes, these groups also determine the long-term alkali resistance, while the silicon functional

groups determine the rate and by-products of the silane's reaction, along with the depth of penetration [18].

The three most common types of silicon-based sealers are Monomeric Alkylkoxysilanes (AS), Oligomeric Alkylkoxysiloxanes (OAS), and Polymeric Alkylkoxysiloxanes (PAS). The length of the alkyl groups (silicon functional) determines the performance capabilities, which are penetration ability and resistance to alkalis. AS are small, can penetrate better, but are quite volatile and therefore need to be applied in high concentrations (between 40 and 100% active ingredients) [13]. A recent study has indicated that this fear of volatility is greatly exaggerated since the rate of reaction and capillary suction are much faster than the evaporation rate [20]. OAS are relatively small molecules which do not evaporate very readily and can be used in smaller concentrations. PAS are larger molecules and do not penetrate very easily as exhibited by one recent report that claimed that only AS and OAS sealers are penetrants [6]. This may suggest that siloxanes, being more stable, would be better used on more porous concrete into which they could penetrate. It is not surprising that siloxanes generally performed rather poorly in an NCHRP study since good quality, fairly dense concrete was used [14]. PAS sealers also need a catalyst to keep the treatment tack-free. All of these sealers are hydrophobic but remain permeable to water vapor [13].

When a hydrophobic agent is flooded onto a concrete surface, several actions occur at once: capillary action draws in the treating liquid, the hydrolyzable groups of

the silane molecules begin to react with one another and with the substrate, and the hydrophobic agent evaporates [20]. The rates of each of these varies depending on the chemical nature of the material.

Silanes and silane-related products have only recently been widely used in this country, though developed in Europe over 30 years ago. Lab results have been varied and field tests mostly successful. Recently, mixtures of silanes and siloxanes have proven to be extremely effective [14]. In one test, the most effective combination of silane in a solvent was a 40% isobutyl trimethoxy silane in ethyl alcohol. Penetration depths varied from 1/25 to 1/3 in (1 to 8 mm), averaging between 1/16 and 1/8 in (1.5 and 3 mm). Chloride ion ingress was not influenced by the depth of penetration, although the long term performance due to protection from ultraviolet light and abrasion is most assuredly related to depth of penetration. It is not recommended that penetrating sealers be applied to concrete previously treated with curing agents, linseed oil, or other nonpenetrating sealers, since the needed penetration ability would be impeded [14].

2.2. Use of Sealers

Even though sealers may be effective, it must be emphasized that "the use of properly consolidated and properly cured low water to cement ratio concrete and deep cover over the embedded reinforcing steel is still needed for long-term protection in

severe environments" [11].

According to their strongest proponents, sealers are economical at almost any time in the life of the deck. If the concrete dries out, which may be accomplished in less humid environments using sealers, corrosion of salt-contaminated concrete will subside [7].

2.2.1. Function and Qualities of Sealers

One of the main reasons sealers are used, which directs this research, is to restrict the ingress of chlorides which initiate corrosion. However, sealers have a number of other uses. The qualities desired in a sealer for fulfilling its purposes are also described below.

2.2.1.1. Purposes Fulfilled by Sealers

As stated, sealers are used for a wide variety of purposes. Since they essentially reduce the permeability of the concrete surface, they can be useful in protecting against any deterioration relating to this property, namely, carbonation, alkali-aggregate reaction, freeze-thaw, and corrosion of rebar [21]. The protection from freeze-thaw damage, for instance, lies in the ability of the sealer to prevent water intrusion while helping the concrete to dry out by being vapor permeable [17]. The Army Corps of Engineers uses sealers for the prevention of erosion encountered in hydrological situations [17]. Protection from salt scaling is considered a use for

sealers [15]. Sealers are also believed to be able to provide waterproofing for cracks up to 0.025 in (0.06 cm) [2].

Along with preventing chlorides from entering concrete and thus initiating corrosion, some authors suggest that the application of sealers to concrete with active rebar corrosion could cause a reduction in the rate of corrosion, thereby extending the life of the structure [7]. For example, one recent research report stated, "We hope to show that the use of a suitable penetrating sealer, applied using sound preparation and application techniques, can effectively improve the rate of deterioration of older structures" [13]. This is thought to occur due to a drying effect which reduces the electrolyte level needed for corrosion. It has not been tested in humid environments, but in arid climates, this appears to work [7].

"By slowing down the rate of corrosion, freeze-thaw microcracking, surface scaling, alkali-aggregate reaction and other problems, sealers can prolong the service life of bridge deck concrete and possibly eliminate rehabilitation within the functional service life span of the bridge" [19].

Although certain sealers can significantly reduce the intrusion of chloride into concrete, it must be remembered that "the use of properly consolidated and cured low water-to-cement ratio concrete, and deep cover over the embedded reinforcing steel is still needed for long-term protection in severe environments" [15].

2.2.1.2. Qualities Desired in a Sealer

There are many qualities which are required of a concrete sealer in order to achieve satisfactory performance. Most researchers and users would list the following qualities as necessary or highly needed: resistance to the absorption of water; resistance to water soluble salts, chlorides in particular; chemically resistant and long-term stability in an alkaline environment; permeability to water vapor; tack-free finish which does not adversely stain or discolor the concrete; measurable depth of penetration (for penetrants); and low health and environmental risk [13,18,20].

The effectiveness of a sealer to perform properly is influenced by the quality of concrete. Research has indicated that, in general, sealers perform better on good concrete with low water-to-cement (w/c) ratios than on poorer, high w/c ratio concrete [6]. Other important factors which affect the performance ability of the sealer include curing conditions, condition and preparation of the concrete surface, and application conditions (ambient conditions and coverage rates). Time and cost are also factors in considering the use of sealers [14].

The depth of sealer penetration itself depends on 1) permeability of the substrate, 2) preparation technique of the concrete surface, 3) amount of solution applied in relation to the level of active ingredient, and 4) penetrating ability of the sealer solution, which depends on the molecular size of the active ingredient, viscosity, and other properties of solvents. Depth, ideally, should be over 1/4 in (6 mm) with recorded depths reaching in excess of 3/4 in (20 mm) [13]. Under identical

conditions, it has been noted that monomeric alkyl silanes proved to be able to penetrate the greatest depths [20]. This is not surprising since they have the smallest molecule size of all the penetrants.

2.2.2. Application

Many sealers are not able to be applied directly to concrete for a variety of reasons. For application purposes, they are dissolved in a solvent. The solvents dissolve and/or lower the viscosity of the sealer and carry the active ingredient. The solvent evaporates after penetration leaving the active ingredient in the pores of the concrete. Solvents used include water, alcohol, mineral spirits and kerosene [13].

The application process is extremely important in the effectiveness of sealers. Even if the "correct" sealer is chosen for a particular job, if the sealer is improperly applied, failure of the protection objectives will occur [22]. Details of ambient conditions, surface preparation, and application rate need to be adhered to strictly.

2.2.2.1. Ambient Conditions

Ambient conditions include temperature and moisture level of the concrete surface and air. Some typical requirements which are made include minimum application temperatures for epoxies (above 40°F, 5°C) and moisture needed after application for silane-based sealers to complete their reactions [13]. Obviously, common sense would also include requirements such as no high winds (which would

disperse any sprayed or volatile sealer) and no heavy rains forecast for the day of the application.

2.2.2.2. Surface Preparation

Preparation of the concrete surface and proper application is of prime importance in influencing the eventual effectiveness of the sealer [10]. Almost any surface in the field needs to have dirt, debris, and chemicals removed in order for adhesion to properly occur between the sealer and the substrate. Sandblasting is commonly specified by manufacturers, but also recommended are water-blasting, low-pressure washing, power brooming, and closed-cycle blasting [13,21].

Arguments against sandblasting include that it only exposes more pores to seal and it is too slow and expensive to be cost-effective in the long run. Therefore, no other surface preparation other than dry brushing would be recommended [21]. Since sealer application needs a dry surface, any surface preparation which would use water would cause a lengthy delay in application while the surface dries.

2.2.2.3. Application Rate

The suppliers of concrete sealers typically include as part of their directions for use, an acceptable range for an application rate. The correct coverage is important since too much material may result in runs and reduced breathability, and too little material will result in inadequate waterproofing. Along with the coverage

rate, uniform application throughout the sealed area needs to be ensured [21]. The rate of application depends mainly on porosity and the texture of the concrete [22]. Many authors suggest trial applications at varying coverage rates in whatever approval test is used.

2.2.3. Costs

Preventive maintenance may be extremely cost effective in the long run. Of all the protective maintenance and rehabilitation options available over the life of the bridge, sealing is by far the most economical at \$.07/ft²/yr (assuming a 7-year life) as compared to \$.40 to \$.60/ft²/yr for other protection methods and much more for any method considered to be a more complete rehabilitation technique [7], as indicated in Table 2.1. Even if the life expectancy is only 2 years, sealers may offer the least costly protection. The major concern expressed by most transportation officials and researchers is whether an effective and uniform chloride barrier is achievable using sealers. If not, then the cost factor argument is obviously pointless.

2.3. Testing Sealer Effectiveness

2.3.1. Lack of Specification Agreement

There is presently no universally accepted standard of concrete sealer

Table 2.1 Alberta Annual Unit Costs of Deck Maintenance Activities [7]

Type of Maintenance or Construction Activity	Unit Cost (\$/ft ²)	Expected Life (years)	Annual Unit cost (\$/ft ² /yr)
Initial Deck Construction (pre-1975 design)	\$ 25.00	20	\$ 1.50
Rehabilitation and Concrete Overlay	\$ 25.00	15	\$ 1.67
Partial Depth Patching	\$ 25.00	15	\$ 1.33
Full Depth Patching	\$ 35.00	15	\$ 2.33
Annual Washing	\$ 0.04	1	\$ 0.04
Asphalt Sealing	\$ 0.25	5	\$ 0.05
Polymer Membrane and Asphalt	\$ 12.00	20	\$ 0.60
Polymer Member/Asphalt Maintained w/ sealing	\$ 13.50	35	\$ 0.39
Temporary Polymer Membrane and Asphalt	\$ 4.00	10	\$ 0.40
Cathodic Protection	\$ 15.00	30	\$ 0.50
Polymer Wearing Surface Class B	\$ 7.00	15	\$ 0.47
Concrete Sealing (silane)	\$ 0.50	7	\$ 0.07
Deck Testing (CSE)	\$ 0.10	5	\$ 0.02

performance. Even ten years after the landmark research project addressing this problem, NCHRP 244, there remains no consensus on any acceptable testing procedure [21]. There is also a lack of in-service data on the performance of concrete sealers, particularly when subjected to wheel traffic [8]. One observer describes this as a Catch-22 scenario. There are no specifications because there is little data, but there is little data because, since no one agrees on a specification, tests are varied and conflicting [23]. According to one author, the lack of standard test procedure for the evaluation of sealers is the most prevalent reason for the slow acceptance of sealers [7]. Even when choosing the proper sealer for protection of a parking garage, the difficulty is compounded by the absence of accepted standards for testing and performance criteria [6].

In a survey of U.S. and Canadian highway agencies, it was found that a wide range of tests, standardized and not, are being used with no approval procedure or test method common to more than a small fraction of the agencies. As seen in Table 2.2, AASHTO T 259, "Resistance of Concrete to Chloride Ion Penetration," is the most common test method used, followed by NCHRP 244, Series II test. Some agencies rely on test data from the vendor for approval [9]. Many other tests are also used and mentioned in section 2.3.2.

Therefore, it is not surprising that many claims of sealer performance have not been justified. But it has also been demonstrated that the same product has yielded different performance abilities on different projects, indicating that the conditions at

Table 2.2 Test Procedure Used in Evaluating Sealers [9]

Testing Procedure	Number of Agencies Using This Method
AASHTO T 259	13
NCHRP 244	9
ASTM C 642	6
Absorption (not ASTM C 642)	6
Rely on Vendor Data	6
Penetration Depth	5
Vapor Permeability	5
Other Tests	5
ASTM C 672	3
AASHTO T 277	2
Freeze-Thaw Testing	2
Skid Resistance Testing	1

various sites may greatly influence their effectiveness [13]. Indeed, a large variety of tests have been conducted with varying methods of interpretation. This only compounds the difficulty of setting specifications.

There will be an effort funded by Britain's Department of Transportation which will attempt to establish a test method to determine the effectiveness of surface treatments in restricting chloride ingress [23].

It is also reported that ASTM is now working on a test method to analyze the durability of silanes and siloxanes in concrete. What this would entail was not reported [19].

2.3.2. Approaches to Setting Standards

Two basic approaches could be used to approve products in a testing scheme. A laboratory test could be designed which would simulate the expected concrete mix, exposure conditions, and sealer application. Alternately, the proposed sealers could be applied to the concrete on site with either in-situ tests performed or samples removed and tested in the laboratory [21].

2.3.2.1. Laboratory Testing Standards

If a standard were produced involving a laboratory test, then what would be needed is accelerated testing which is reliable [23]. Alternately, a test which would simply analyze the sealer according to some set parameter which is related to

durability could be used. Of course a correlation between the parameter and durability would need to be derived.

Concrete test specimens for laboratory testing should always be made of a similar mixture as the expected mixture and trials should be performed with different sealers because sealers perform differently with different concrete mixtures [6].

The NCHRP 244, AASHTO , and ASTM standardized tests fall into the category of laboratory testing standards. These will be discussed later.

2.3.2.2. In-Situ Testing Standards

At present, very little work has been conducted on in-place field testing of sealers [9]. A number of tests have been recently developed, few of which are used. For in-situ testing, sealers should be chosen for each structure after trial application testing. A periodic testing program should also be initiated [14]. In Germany, it has been the practice to test at least three products on the same bridge before deciding on the best alternative: however, the method of testing was not described by the author discussing this approach [24].

One method to test the effectiveness of sealers which has been applied is to take cores (2.75 in [70 mm]) from the sealed concrete and measure depth of penetration, chloride ion content profile for various depths (both present and after ponding), and water absorption characteristics. Two cores should be taken for comparison of sealed to unsealed concrete after the sealer from one core is removed.

A 15% sodium chloride solution is ponded for 21 days with the cores weighed at 1, 3, 7, 14, and 21 days and after which the chloride ion content profile is again determined. Initial chloride profile gives a sense of the contamination level of the concrete and the effectiveness of the sealer so far, particularly if a control section on the concrete structure is also analyzed. Weight gain during ponding yields information about the future effectiveness of the sealer for protecting the concrete. The chloride content profile of the sealed to unsealed surface after ponding should give an indication of the protection against chloride intrusion in the future. It is thought that these tests could be used to predict the future effectiveness of the sealers. They should also be used in determining the correct sealer for the concrete and environment [14].

One simple field test devised in Great Britain and described by Carter involves caulking a clear plastic tube vertically to the concrete surface, filling with water, and noting the drop over time [21].

2.3.3. Present Testing Methods Used

The landmark report most noted for beginning to address the question of standardizing sealer tests was NCHRP 244 [15]. Its goal was to investigate the effectiveness of various generic types of chemical surface sealers applied to concrete under different environmental conditions. The authors stated, however, that the report did not apply to sealers applied to bridge decks since they are subject to

abrasion from traffic [15].

The measured parameters of NCHRP 244 include resistance to water absorption, vapor permeability, resistance to chloride intrusion, depth of penetration, and resistance to abrasion and ultraviolet light. All of the results are compared to control cubes. Also measured were the performances of the same sealers in the same tests on cubes which were already treated with linseed oil. This was to simulate the condition of many existing structures which have been similarly treated in the past. Also considered were the potential safety hazards, economic feasibility, esthetics of the surface after application, and application techniques and costs [15].

Most of the nonstandardized laboratory tests surveyed followed similar approaches as found in NCHRP 244, measuring similar parameters. However, other less-measured parameters for determining sealer effectiveness include carbon dioxide permeability, freeze-thaw resistance, skid resistance, and scaling [9].

Other standardized laboratory tests which are common include AASHTO T 259, ASTM C 642, ASTM 672, and AASHTO T 277. These tests, however, were not designed specifically for the testing of sealer effectiveness as was NCHRP 244.

"Resistance of Concrete to Chloride Ion Penetration," AASHTO T 259, is commonly referred to as the "90-day ponding" test. The specimens analyzed are slabs which are subjected to 90 continuous days of ponding with a 3% sodium chloride solution. At the end of this period of time, the chloride content is measured at two depths, 0.0625-0.5 in. (0.16-1.3 cm) and 0.5-1.0 in. (1.3-2.5 cm). These

values, subtracted from baseline values measured, are reported. Abrasion by sandblasting or grinding is required if the concrete will be subjected to traffic wear. This test is not intended to give an estimate for the service life of a type of concrete (or sealer) and no quantitative limits on the measured data were suggested [25].

The other AASHTO specification employed (T 277), "Rapid Determination of the Chloride Permeability of Concrete," analyzes 3.75-in (9.5-cm) cores by measuring the amount of charge passed through the 2-in (5.1 cm) long sample in 6 hours of exposure to a 60-V dc current. One end of the core is immersed in a sodium chloride solution. The total coulombs of charge passed is related to chloride permeability, with ranges for high, moderate, low, very low, and negligible. (These limits were adopted from FHWA/RD-81/119 [26].) In research which attempted to compare this method with the 90-day ponding test, it was found that a general agreement in ranking of sealer effectiveness is apparent, with the rapid test being conservative in the case of more effective sealers (as compared to control specimens). The rapid test may also be able to indicate differences between sealers not seen in the longer test [27].

The two ASTM specifications used by some highway agencies do not attempt to measure chloride permeability, but only measure parameters which have been related to sealer effectiveness. ASTM C 642, "Standard Test Method for Specific Gravity, Absorption, and Voids in Hardened Concrete," measure the parameters mentioned in the title. The absorption measurement is for water, not a solution, and is performed by immersing a specimen (at least 28 oz, 800 g, for normal weight

concrete) in water for as many days as it takes to reach a constant surface dry weight [28]. ASTM C 672 is a measure of the salt scaling tendency of concrete [29].

2.3.4. Parameters Measured

The properties mentioned in the discussion of NCHRP 244 are commonly measured. These parameters will be discussed as to typical methods of testing and possible variables involved in the results. A few other parameters which have been measured are also discussed.

Specimen preparation for NCHRP 244 is common for similar testing procedures. Concrete (5000 psi, 0.53 w/c, 4-5% air, and 3-in. [8-cm] slump) are cast in 4-in. (10-cm) cubes, sandblasted after 7 days of moist curing and allowed to air cure for an additional 21 days. The weight loss from saturated condition is plotted. The sealers are then applied and allowed to cure for 14 days [15].

2.3.4.1. Water Absorption

The cubes are then immersed in a 15% sodium chloride solution. With the saturated surface dry weight taken every 3 days, the cubes are kept immersed for 21 days. The difference in weight over time is the measure of the water absorption capability of the specimen. As with the other parameters, a comparison is made with the control specimens [15].

It has been noted that higher w/c ratios yield higher porosities. The top layer

of the cubes which are usually cast in this type of examination had a greater porosity than any other part of the cubes. Therefore, a submersion water permeability is an optimistic estimate of the true effectiveness of the sealer since 5 of 6 faces are less permeable than will actually be exposed [6].

2.3.4.2. Vapor Permeability

Saturated specimens, as attained at the end of the previous procedure, are used for vapor permeability measurements. This is simply measured by weight loss being tracked during 24 days of drying. This is typically done in an environment common to the field, i.e. no heating or zero humidity applied [15].

2.3.4.3. Chloride Ingress

By submersion in a sodium chloride solution when testing for water permeability, the chloride penetration of a specimen could be measured in the same test. After vapor permeability is measured, the cubes are split and half of each 4-in. (10-cm) cube is used to determine the chloride content. It was found that, for the most part, there is a linear relationship between water absorption and chloride ingress. Only a few of the sealers tested in NCHRP 244 could be viewed as "chloride screens," that is, better at preventing chlorides from entering the concrete than water [15].

The three tests above are often used to screen samples for further testing.

2.3.4.4. Resistance to Abrasion and Ultraviolet Light

Resistance to field conditions such as abrasion and ultraviolet light exposure are simulated in a variety of ways. NCHRP included an accelerated weathering test using saltwater ponding and ultraviolet exposure to give a more reasonable similarity to southern saltwater climates. This was done for 24 weeks. A northern climate was simulated by 24 5-day weeks of freezing the samples along with less exposure to ultraviolet light. The amount of ultraviolet light used in the two tests was estimated from amounts typically received in those climates they were simulating [15].

The Alberta test method is typical of all tests reviewed which attempted to simulate traffic abrasion. This is done simply by sandblasting [19]. The amount of sandblasting in terms of time or depth of scarification is not typically given. Field testing could be done to analyze the effect of wheel traffic on sealer durability. These would be much longer tests, as could be surmised.

2.3.4.5. Depth of Penetration

When analyzing penetrating sealers, it is important to ensure that the sealer does penetrate to a satisfactory depth. This can be done by core samples from the field or laboratory samples. When a cut vertical surface is wetted, the depth of penetration can easily be identified since there will be a layer of the cut face near the surface which resists wetting. Penetration depth is useful in determining the presence and uniformity of the sealer [14].

2.3.5. Suggested Standards from Literature

Recommended specifications from the NCHRP 244 test were >75% reduction in weight gain and chloride ion content at the end of testing (compared to control cubes). After the cube series "Screening Test", an "Accelerated Weathering" test was recommended. The recommended standard for this test was >90% reduction of chloride ion content [14].

In one recent attempt to set standards, the basic parameters which are of concern are listed with the suggested limits in parentheses:

- penetration depth (no standard)
- water absorption (1% max)
- moisture vapor permeability (95% min)
- chloride penetration (.02% max at 0.5-1.0 in. depth)
- salt scaling resistance (0.16 lb/ft² mass loss max) [8].

2.3.6. Great Britain's Approach to Setting Standards

Recent regulations by the Department of Transportation of Great Britain recommended that all bridges be treated with penetrating sealers and went on to specify that only monomeric alkyl (isobutyl) trialkoxysilane be used. Over 1 million liters of silane were expected to be applied to bridges in 1991. Many contractors were quoted speaking of the difficulty of application of silanes. The depth of penetration has also been brought into question, along with the effectiveness as

compared to a silane/siloxane mix. A new organization, Silane Impregnators Association, was to have begun which would begin to answer some of the questions surrounding the use of silane on concrete surfaces [30].

This restriction to one type of product has drawn much protest by manufacturers and researchers alike who say that performance specifications should be invoked instead of a product specification [30].

German officials also have been disturbed by Britain's product or material specification instead of a performance specification. A recent research venture has begun which will first attempt to "develop a reliable non-destructive test to prove the penetration of treatments in concrete." This test will then be used on different products for specification purposes [24].

Peter Robery [10], a head engineer for a consulting firm in England, argues that the material specification is valid since the smaller silane molecule is needed in the high cement concrete which is typical for Britain's bridges. He emphasizes the need for proper application by qualified individuals, especially in light of the difficulty which he admits of environmental and application restrictions. He suggests water uptake tests be used to determine if the product was applied properly.

2.4. Measurement Technique for Present Research

2.4.1. Chloride Content Using Ion Selective Electrode (ISE)

2.4.1.1. Collecting Samples

As described in AASHTO T 260, "Sampling and Testing for Total Chloride Ion in Concrete and Concrete Raw Materials", there are basically two methods to collecting concrete samples for the analysis of chloride content. The first method involves cutting slices from the desired depths and crushing or pulverizing the sample to pass through a number 50 sieve. The second method requires a rotary hammer with a depth indicator which pulverizes the sample as it collects it. If the collected powder does not pass through a number 50 sieve, then additional crushing is needed [31].

2.4.1.2. ISE measurements

Two options are available for the analysis of the acid-soluble chloride content in a laboratory. ASTM C-114 is a method which requires 10 g of sample and uses silver nitrate to titrate the digested solution in order to determine the amount of chlorides in the sample. The titration is done using an ion sensitive electrode (ISE) [32]. Alternately, a method derived by Virginia Tech, the rapid chloride determination method, uses an ISE to measure the millivolt level in a digested sample

solution. It only requires 3 g of sample and is much quicker than the titration method. The results of this method are derived from correlation to the ASTM standard.

2.4.2. Surface Absorption Test

2.4.2.1. British ISAT

Many methods have recently been developed to attempt to measure the permeation properties of concrete on site. Most of these are far from being perfected. The Initial Surface Absorption Test (ISAT) as described in BS 1881 has been used extensively [33].

The Surface Absorption Test (SAT) used in the present research is extremely similar to the British Initial Surface Absorption Test (ISAT) which was developed over 20 years ago. The ISAT has been tested in the laboratory on various materials including bricks, mortar, and concrete.

As with the SAT device, the ISAT device has a water reservoir, tube intake, stopcock, water cell, capillary tube and scale. The capillary tube with the scale, however, is horizontal which keeps a constant head. With research beginning in 1956 on this type of measurement, the ISAT was developed in order to test the cover concrete, whose characteristics could not be truthfully determined using the higher pressure of the standard, destructive permeability test. In earlier studies which

examined the relationship between the ISAT and other tests standards, a good correlation was found with the destructive absorption test [34].

An assessment of waterproofing materials and air entraining agents was also conducted. Before this, users usually only checked the effectiveness of sealing agents by pooling the water on the surface and watching it move like mercury. It was reasoned that the ISAT was a much better simulation of field conditions with the 200 mm head being equal to a 120 m.p.h. wind and rain speed (worst case) [34].

Test limits were proposed to differentiate between acceptable and failed concretes. These limits were not directed toward sealers. The limits proposed were not based on the amount of water absorbed but the rate it was being absorbed at 10 minutes and 1 hour after the beginning of the test [34].

2.4.2.2. Factors Affecting Performance

Since the properties of the near-surface concrete have been increasingly recognized as very important in contributing to the durability of the concrete, it is suggested that studies should focus on the understanding of variables which affect present testing methods. A modified version of the British ISAT was utilized to test the surface absorption properties of concrete, and analyze the factors that affect the readings which include the following: 1) The water/cement ratio and the curing of the concrete greatly affect the 'ultimate' absorption value, and 2) the temperature and duration at which the specimen dries before conducting a surface absorption test has a

great influence on the absorption value measured. For stable readings, the following drying conditions should be met: 1) 4 days at 105°C, 2) 10 days at 50°C, or 3) minimum 7, preferably 14 or more days, at 20°C, or on site conditions. "This highlights a serious drawback to the BS ISAT method, as the values obtained may not reflect the quality of concrete so much as the ambient condition." However, "the test gives sufficiently reliable results when the moisture condition of the concrete is constant" [33].

2.5. Service Life Predictions

Very little is mentioned in the literature regarding the service life of sealers. It is known that they obviously do not last the entire life span of the structure. But how long they are effective to any acceptable level is rarely mentioned. Life expectancy for sealers used on decks is typically based on surface abrasion, or traffic volume. Estimating life expectancies is the most difficult part of evaluating different methods of protection schemes. Approval tests and accelerated tests for concrete sealers are needed for predicting life expectancies [7].

In a conversation with Paul Carter, maintenance engineer for Alberta Transportation and Utilities, an indication of sealer service life in practice was attained. Carter, a strong proponent of using sealers for concrete protection, said that bridges on major routes are resealed every 2 to 4 years, while bridges on less traveled

roads are resealed on a 6 to 8 year cycle. No in-situ testing is done to check the validity of these decisions; wisdom gained by experience and budget concerns are the only input.

3.0

RESEARCH DESIGN

3.1. Sealer Selection

Four sealers were chosen from the most common and promising generic groups. These groups were water-based epoxies, solvent-based epoxies, silanes, and siloxanes. After both surveying the approved list of sealers from Alberta Transportation and Utilities, and discussing with the Materials Engineer the approved sealers used in Virginia, the particular brand within each generic group was chosen.

Epoxies were chosen since it is known that they have been and are still quite popular. It is acknowledged, however, that epoxies are classified as coatings and most should not be used on bridge decks due to their lack of resistance to traffic abrasion and ultraviolet light. (Some are applied on decks, a few show good resistance to abrasion.) Many epoxies also change the color of the concrete or appear glossy and reduce skid resistance. Even then, epoxies are often used to protect bridge components from chloride ingress. Due to environmental concerns and restrictions, much effort has been extended in the development of water-based epoxies. This trend will only continue considering the atmosphere of our environmentally-minded society.

Silanes and siloxanes, which are closely related chemically, have been developed over the past 30 years, but a great amount of effort has been exerted only in the past decade focusing on factors such as their effectiveness, penetration, and application. These types of sealers, considered penetrants by most, are more resistant to abrasion and ultraviolet light exposure. Recently, mixtures of the two have become popular as well, along with their use as primers for other types of sealers. Linseed oil was not chosen to be tested since, as noted earlier, its popularity has been decreasing due to its poor performance in other testing programs.

3.2. Concrete Mixture and Specimen Design

3.2.1. Concrete

The concrete mixture design was as indicated in Table 3.1 for both the slab and wall specimens. The desired water to cement ratio was 0.47 with a slump of 3-4 inches (7.5-10 cm), and a 4000 psi (34.5 MPa) strength. The slump was measured to be 5 in. (12.7 cm) and air content was 5.4%. The density was determined to be 148 lb/ft³ (2370 kg/m³) and the 28-day compressive strength was found to be 5570 psi (38.4 MPa).

Table 3.1 Concrete Mixture Design for Slab and Wall Specimens

	lb/yd ³ of concrete	kg/m ³
Cement	640	380
Water	301	179
Aggregate		
coarse (#57 limestone)	1750	1038
fine (manufactured sand)	<u>1280</u>	<u>759</u>
TOTAL	3971	2356

3.2.2. Specimen Preparation

Three different specimen types were used to assess sealer performance. Horizontal surfaces, outdoor laboratory slabs, were cast simulating bridge decks. Vertical surfaces such as found on piers and pier caps were simulated on an outdoor laboratory wall. Test sections on existing bridge decks in the field were also used to determine the influence of traffic on sealer performance.

3.2.2.1. Horizontal Specimens

Fifteen concrete slabs were cast in order to have three slabs per treatment including three control slabs. The slab dimensions were 36x36x4 in. (91x91x10 cm) as seen in Figure 3.1. Reinforcing steel (#4's) was included for control of temperature and shrinkage cracking. In one direction, the rebar protruded out of the sides of the specimens. This was done to make the moving of the slabs easier. The steel was placed to attain a 2.5-in. (6.35-cm) cover in order that corrosion would not occur during the testing or interfere with sampling.

3.2.2.2. Vertical Specimens

One wall was constructed which served as the surface of all four treatments and the control section. A footer was placed, and standard wall forms were used to cast a 1-ft (0.3-m) thick wall, 6 ft (1.83 m) high, and 16 ft (4.88 m) long, as shown in Figure 3.2. Reinforcement was included for temperature and shrinkage volume

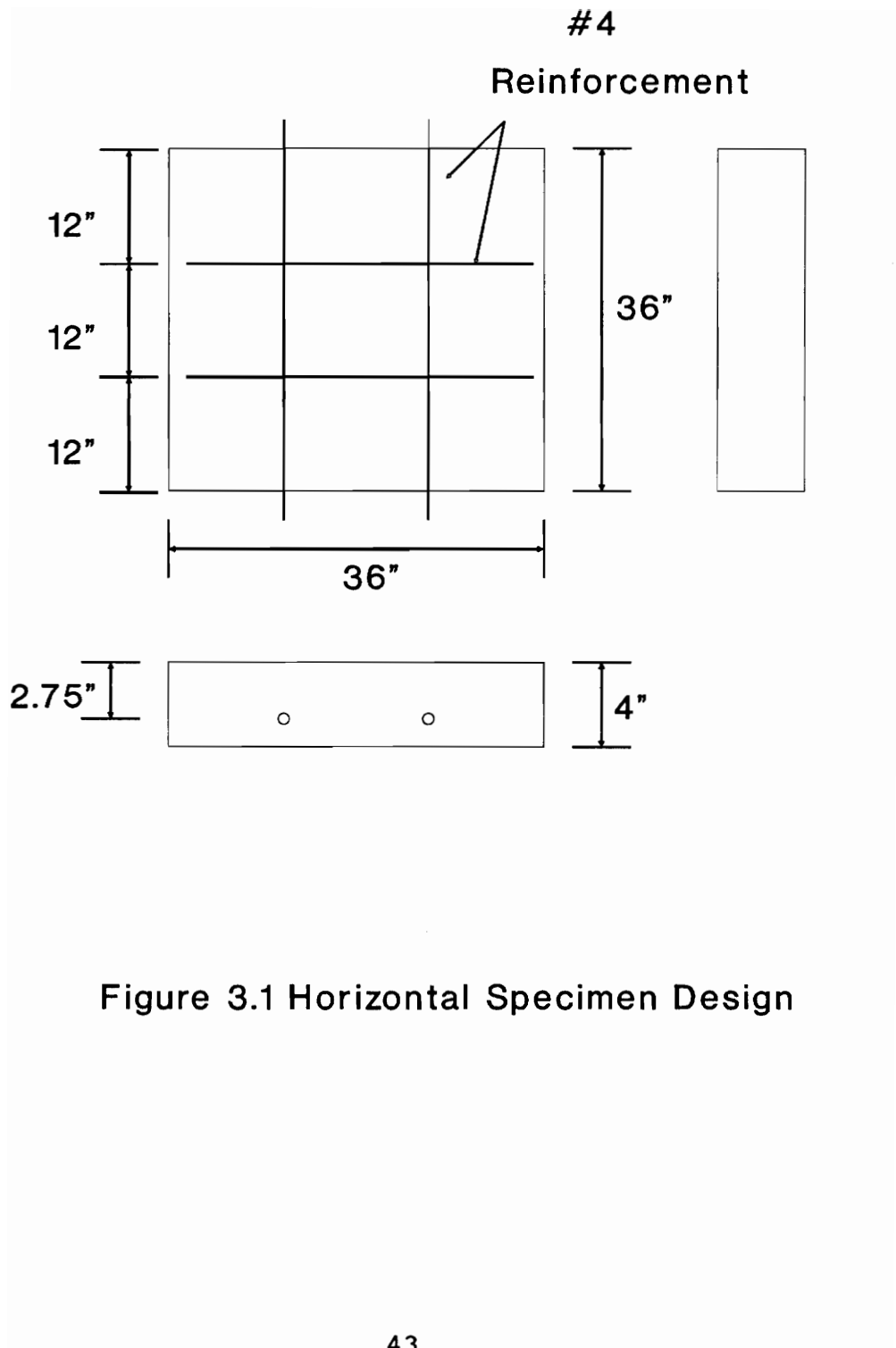


Figure 3.1 Horizontal Specimen Design

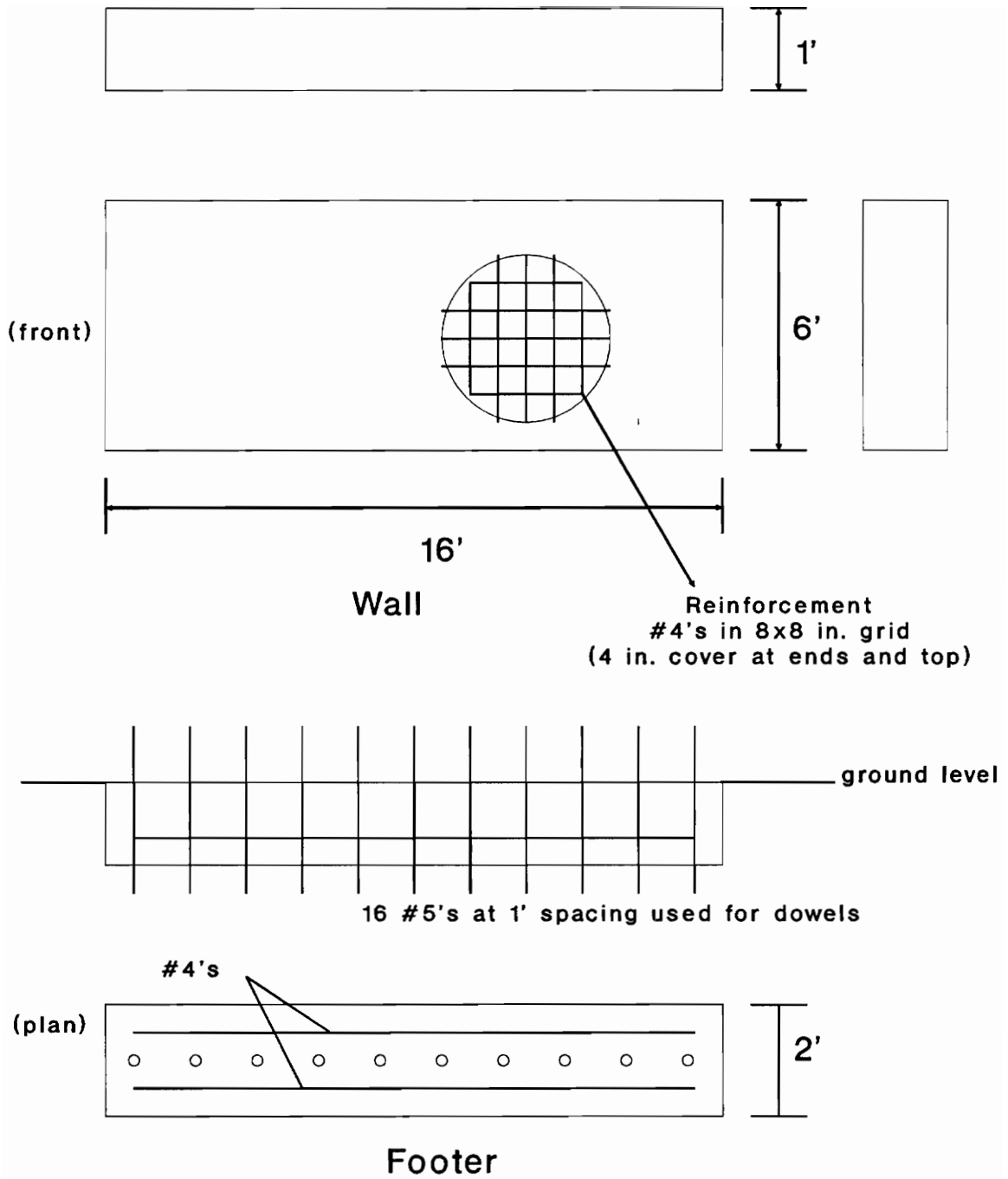


Figure 3.2 Vertical Specimen Design

changes and for structural stability. The wall was secured to the footer through the reinforcement extending out of the base through the footer and by a key along the length of the wall-footer border.

3.2.2.3. Field Assessments

Two bridges, one classified as high volume and one considered moderate, were selected in order to discern the effect on sealer performance of field variables not simulated in the laboratory.

The high volume bridge is located on north bound Interstate 81 over Highway 611 about one mile (1.6 km) south of the Dublin, VA interchange. Its average annual daily traffic (AADT) is approximately 24,270 (1990). The surface of the deck was smooth and was originally placed in 1965. At the time of this study, aggregate was visible due to wear, particularly in the wheel paths. The moderate volume bridge is located near Radford, VA, and is the new east bound Pepper's Ferry Road (Highway 611) bridge crossing the New River. The entire bridge, including the deck, was built in 1990. The surface was tyned. The AADT was approximately 12,430 in 1990.

3.3 Experimental Design

3.3.1. Horizontal Specimens

Fifteen slabs were constructed as described above. As depicted in Figure 3.3,

Control	S1	S2	S3
Water-based Epoxy	S4	S5	S6
Solvent-based Epoxy	S7	S8	S9
Silane	S10	S11	S12
Siloxane	S13	S14	S15

Figure 3.3 Horizontal Specimen Assignment

three slabs were used for control specimens, with each of the four sealers tested being applied to three slabs as well.

3.3.1.1. Concrete Placement and Curing

The concrete for the horizontal specimens was broom finished. The slabs were demolded after 3 days and placed outside on top of concrete blocks in order to better simulate a deck condition. The concrete was moist cured for seven days using wet burlap and plastic covering. This was followed by 24 days of air curing.

3.3.1.2. Sealer Application

The sealers were applied 31 days after the concrete was cast. The high temperature for that day was approximately 60°F (16°C), and the weather was partly cloudy with little wind. The sealers were applied, in accordance with the manufacturers' instructions. Sandblasting was performed to prepare the surface. The application rates were chosen in the middle to upper middle range within the allowable limits for all the sealers. Table 3.2 displays the application rates along with the method of application for the horizontal laboratory specimens, bridge deck test sections, and vertical laboratory test sections.

The silane and the siloxane treatments did not change the appearance of the slab surface. The water-based epoxy caused the surface to appear glossy. The solvent-based epoxy had a slight glossy look, but the color was darker and duller than

Table 3.2 Sealer Application Rates and Method for Horizontal Laboratory Specimens, Field Bridge Deck Sections, and Vertical Laboratory Test Sections

Horizontal Specimens and Field Bridge Deck Test Sections	Coverage Rates		Application Method
	ft ² /gal	m ² /l	
Water-based epoxy	150	53	-brush used on horizontal specimens -roller used on field test sections
Solvent-based epoxy	(coat 1) 250	88	brush
	(coat 2) 375	132	
Silane	135	47	low pressure pump
Siloxane	110	39	flood and brush

Vertical Specimens	Coverage Rates		Application Method
	ft ² /gal	m ² /l	
Water-based epoxy	150	53	brush
Solvent-based epoxy	(coat 1) 250	88	brush
	(coat 2) 375	132	
Silane	135	47	low pressure pump
Siloxane	150	53	low pressure pump

the water-based epoxy surface. Similar changes to the concrete surfaces due to sealer application occurred on both the vertical specimens and bridge decks.

3.3.1.3. Ponding

After application, the slabs were leveled in order for salt water ponding to be uniform throughout the slab. Dikes were made out of 1/2-in. (13-mm) thick insulating styrofoam cut to 1-1/4 in. (32 mm) high. The styrofoam was adhered to the concrete surface using silicone sealant.

Surface Absorption Test, (SAT), [12] measurements were taken as a reference, and ponding was then started. A summary of the ponding cycles is presented in Table 3.3.

Salt water (3% by weight of sodium chloride) ponding of the horizontal specimens included three continuous days (72 hours) of saltwater exposure followed by four days of air drying. This allowed for a more reasonable approximation of the alternating wet and dry conditions found in the field. The lower ponding times in some of the first seven cycles were a result of extremely cold temperatures forcing removal of the solution over night in order that the dikes not be destroyed from ice expansion. The average depth of the water on the slabs was just over 5/16 in. (0.8 cm). Plexiglass sheets were placed over the ponded slabs in order to prevent rain or snow from entering and evaporation from occurring which would change the concentration of the solution.

Table 3.3 Periods of Salt Water Ponding for Laboratory Slabs and Surface Wetting for Wall

Ponding Cycle	Slab Cycle	Hours of Exposure		Wall Cycle	Cumulative
		Cumulative	Cycle		
1	20.5	20.5	20.0	20.0	20.0
2	24.5	45.0	24.5	44.5	44.5
3	86.75	131.75	28.5	73.0	73.0
4	23.75	155.5	23.75	96.75	96.75
5	24.5	180.0	24.5	121.25	121.25
6	72.5	252.5	24.5	145.75	145.75
7	14.0	266.5	14.0	159.75	159.75
8	72.25	338.75	24.25	184.0	184.0
9	74.75	413.5	22.25	206.25	206.25
10	74.0	487.5	24.75	231.0	231.0
11	72.5	560.0	21.5	252.5	252.5
12	73.0	633.0	24.5	277.0	277.0
13	72.0	705.0	28.5	305.5	305.5
14	73.25	778.25	24.0	329.5	329.5
15	74.75	853.0	19.0	348.5	348.5
16	72.0	925.0	19.25	367.75	367.75
17	72.25	997.25	23.75	391.5	391.5
18	72.0	1069.25	23.75	415.25	415.25
19	72.5	1141.75	24.0	439.25	439.25
20	72.25	1214.0	24.0	463.25	463.25
21	72.25	1286.25	24.0	487.25	487.25
22	72.0	1358.25	23.75	511.0	511.0
23	72.5	1430.75	24.0	535.0	535.0
24	72.25	1503.0	24.0	559.0	559.0
25	72.25	1575.25	24.0	583.0	583.0
26	72.0	1647.25	14.5	597.5	597.5
27	71.75	1719.0	33.5	631.0	631.0
28	72.25	1791.25	24.0	655.0	655.0
29	72.25	1863.5	24.5	679.5	679.5
30	72.25	1935.75	23.5	703.0	703.0

During cycle 17, it was noticed that since the weather was warmer and the sunlight more direct, the plexiglass coverings held the radiant heat in and began to produce uncommonly high temperatures of the water on the specimen. This was immediately corrected by removing the cover during hot, sunny days. By the 19th cycle, white plastic sheets were placed over the plexiglass covers. This reduced the temperature during hot days markedly.

3.3.2. Vertical Specimens

The 16-ft (4.88-m) wall was sectioned off as shown in Figure 3.4. Six test sections were actually created, one more than the other specimens. This was to test a more recently developed "environmentally safe" silane-siloxane mixture sent on a complimentary basis by a vendor.

3.3.2.1. Concrete Placement and Curing

The wall was cast from the same batch of concrete as the slabs, and therefore, the concrete had the same slump, air content, density, and compressive strength as indicated earlier. A cover was placed over the surface of the wall and the forms and cover were kept on the wall for 7 days. It was also air cured for a total of 24 days before sealer application.

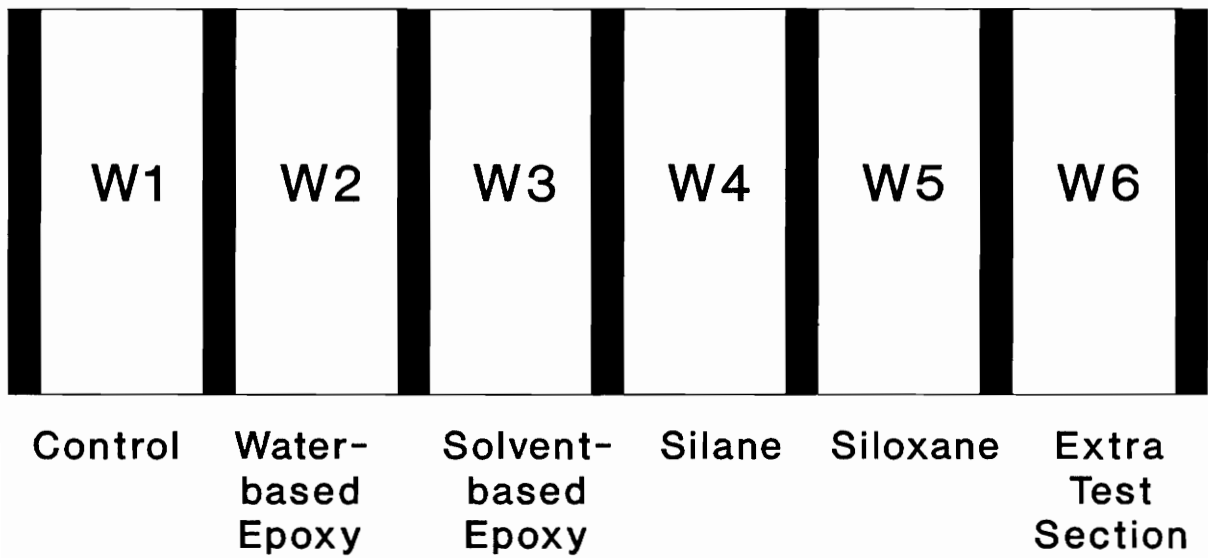


Figure 3.4 Vertical Specimen Assignment

3.3.2.2. Sealer Application

The sealers were applied to the wall 31 days after concrete placement, at the same time as sealers were applied to the slabs. Before sealer application, two 4-in. (10.2-cm) wide duct tape strips were placed vertically 4 in. (10.2 cm) apart to separate the sections. Red spray paint was applied to the open area to produce a noticeable division. The duct tape was removed after sealer application. The surface was prepared by sandblasting. The application rate was identical to that of the horizontal specimens with the exception of the siloxane treatment, which had a different manufacturer's suggested coverage range for vertical surfaces. These rates are presented in Table 3.2, along with the method of application.

3.3.2.3. Surface Wetting

Wetting of the vertical specimens was accomplished by allowing a 3% by weight sodium chloride solution to run down the middle of the wall section. This was accomplished by circulating saltwater over the wall and into a plastic gutter which would direct it into a basin where a pump would send the water to the top of the wall and disperse it in a 4-in. (10-cm) PVC pipe. This pipe had holes drilled in it for the saltwater solution to exit and run down the wall again. There were seven 0.0625-in. (0.159-cm) holes equally spaced over the center 6 in. (15 cm) of each section. Hard plastic sheets were needed to direct the path of water toward the center of each section in order for greater uniformity between sections. The stream averaged 4.0-

6.0 in. (10-15 cm) in width. The flow rate for each section was approximately 0.24 gpm (0.015 l/s).

The typical wetting cycle involved three 8-hour days of wetting followed by 4 days of air drying. As with the ponding cycles of the slabs, the earlier wetting cycles were shortened due to extremely cold weather. Some weeks involved two 12-hour days due to difficulties caused by heavy rains. A summary of the wetting cycles for the vertical specimens is found in Table 3.3.

3.3.3. Field Assessments

The field test sections covered 3-ft (91-cm) strips on the bridge deck extending from the edge of the shoulder across the driving lane side to the middle line. The strips on Interstate 81 were skewed with respect to traffic in order to be aligned with the direction of the bridge skew.

3.3.3.1. Sealer Application

The sealers were applied on consecutive days for the two bridge decks. The temperature both days was in the 50-55°F (10-13°C) range. A similar scheme of separating the sections using duct tape was used on the bridges as was used on the wall, only no paint was applied due to the fact that they were bridges in service. Paint marks on the parapets were made to ensure proper location of the sealers in the future, although the discoloration of the surface by the sealers and the sandblasting

was apparent throughout the test. Methods of application and coverage rates were the same as for the horizontal specimens at the laboratory and are presented in Table 3.2.

3.3.3.2. Salt Exposure

Since the field test sections were to be analyzed by SAT analysis, no data on salt exposure of the bridges was collected during the winter. In an attempt to gather this information for later use, it was found that records of number of applications and amount of each application are not carefully kept by the Department of Transportation. It was estimated by local bridge maintenance workers that the bridge decks in question received between 15 and 25 deicing salt applications after the surfaces were treated with sealers.

It should be noted as well that the Pepper's Ferry bridge is not in the primary route system. Therefore, when deicing is performed, a mixture of sodium chloride and abrasive gravel is used. This is in contrast to the pure sodium chloride used on Interstate 81.

3.4 Evaluation Methods

3.4.1. Surface Absorption Test

As mentioned, the secondary goal of this research was to test the plausibility

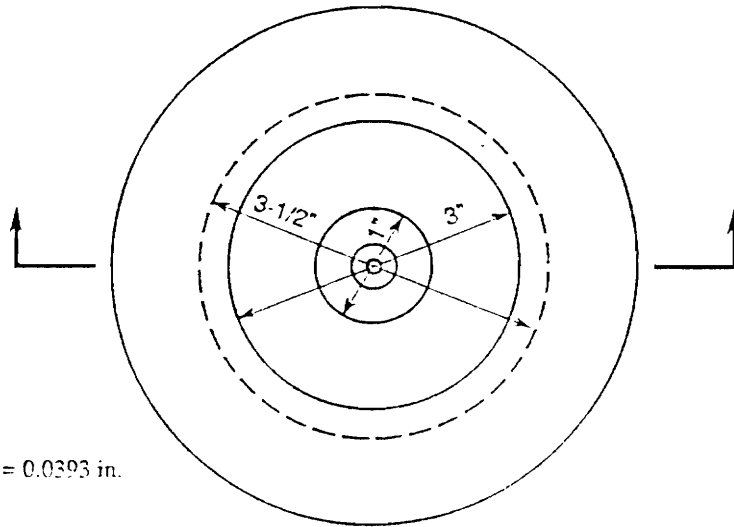
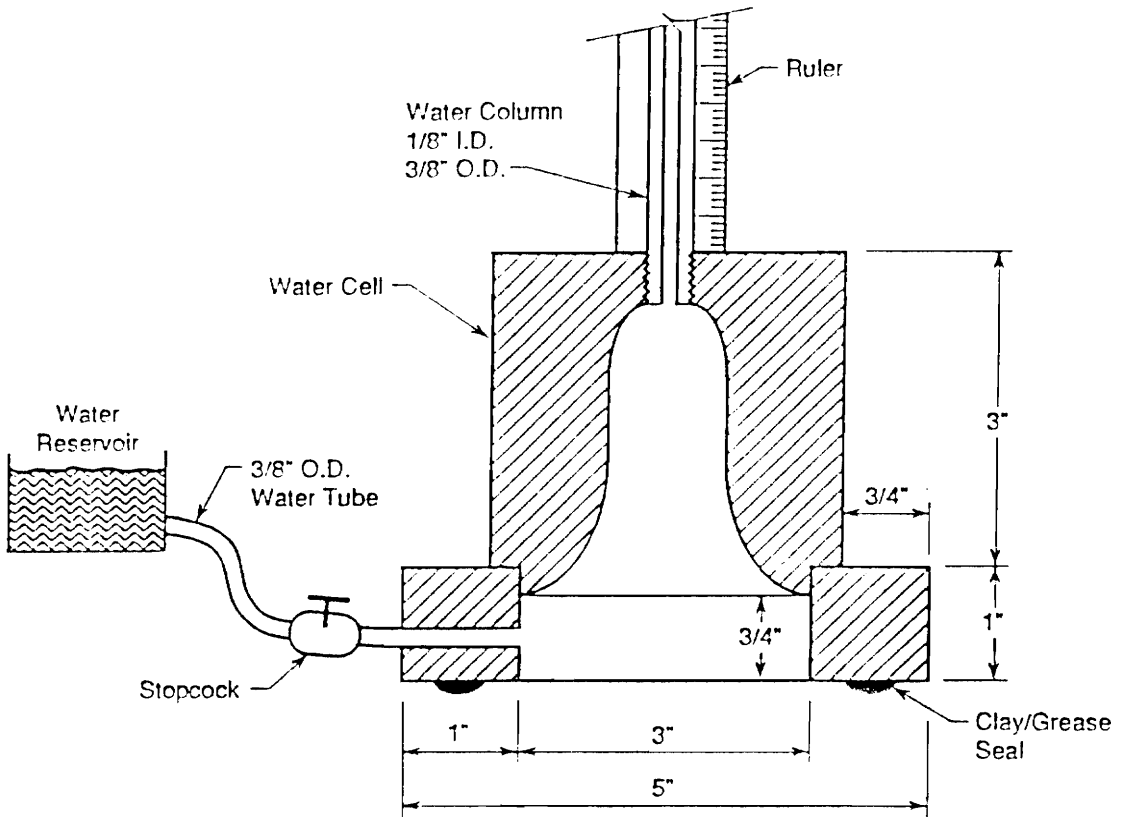
of using the SAT as a rapid, nondestructive test for sealers by examining the relationship between SAT and chloride ingress. This was done by analyzing the laboratory specimens with both methods.

3.4.1.1. SAT Device and Test Procedures

A schematic of the two devices used, which were designed by Construction Technology Laboratories, is shown in Figures 3.5 and 3.6 [12]. The horizontal SAT device is extremely similar to the RILEM device used for the same purposes. It is also quite similar to the British ISAT (Initial Surface Absorption Test) device. The test method involved attaching the water cell to the concrete surface by using a mixture of clay and grease, though plumber's duct seal worked well for the first tests. Water was then allowed to flow into the cell and up the capillary tube to a height of approximately 16 in. (40 cm). The reservoir was then clamped off from the cell using a stopcock and the test time was started. The drop in the column of water in the capillary tube was recorded every minute for 10 minutes. This same procedure was used whether the test section was a horizontal or a vertical surface.

3.4.1.2. SAT Measurement Plan

The original measurement plan was to include a number of base measurements taken before ponding commenced and measurements taken every 3 to 4 weeks during the 30-week investigation. However, due to weather conditions and difficulties in the



Note: 1mm = 0.0393 in.

Figure 3.5 Horizontal Surface Absorption Test Device [12]

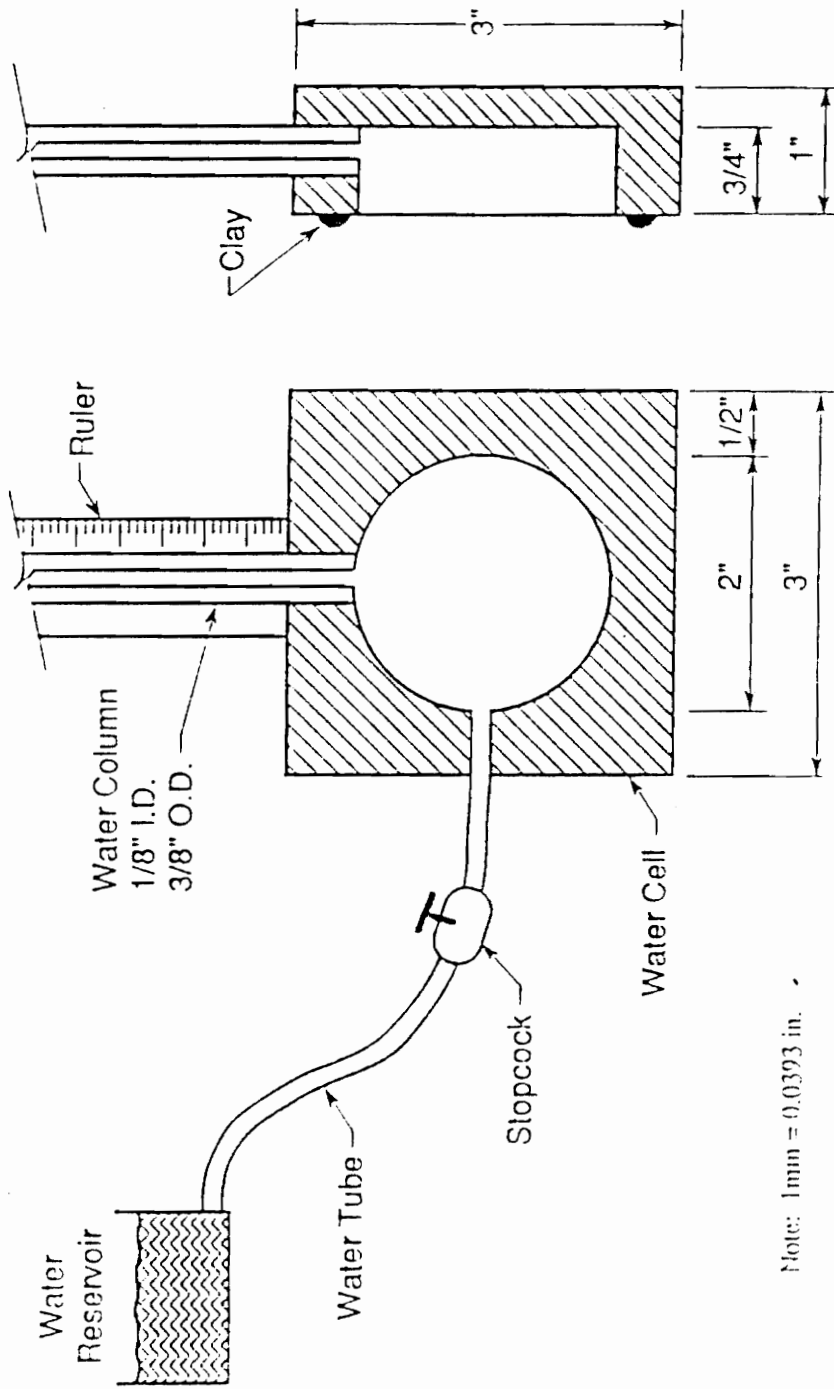


Figure 3.6 Vertical Surface Absorption Test Device [12]

test procedure (as will be described in Chapter 4), only three sets of partial readings could be taken after ponding began.

3.4.2. Chloride Penetration

Chloride ingress was the major measured parameter for the laboratory specimens. The sampling scheme and technique is described, along with the method for chloride analysis.

3.4.2.1. Concrete Sampling Procedure

Concrete samples were collected using an impact drill with a 1-1/8 in. (2.86 cm) bit and a vacuum to collect the pulverized concrete in a filter. Every time a sampling hole was drilled, the top 1/4 in. (0.64 cm) was discarded due to the high chloride content variability that is known to occur in this depth range. Each sampling hole, horizontal or vertical, involved taking samples from four different depths in order to attain the chloride ion profile. The four depths were depth 1 - 0.25 to 0.75 in. (0.64 to 1.9 cm), depth 2 - 0.75 to 1.25 in. (1.9 to 3.2 cm), depth 3 - 1.25 to 1.75 in. (3.2 to 4.4 cm), and depth 4 - 1.75 to 2.25 in. (4.4 to 5.7 cm). These are illustrated in Figure 3.7.

Background chloride content measurements were made by sampling the concrete from one 2-in. (5-cm) deep drilled hole in each specimen, horizontal and vertical. The samples from the horizontal specimens were taken from the sides of the

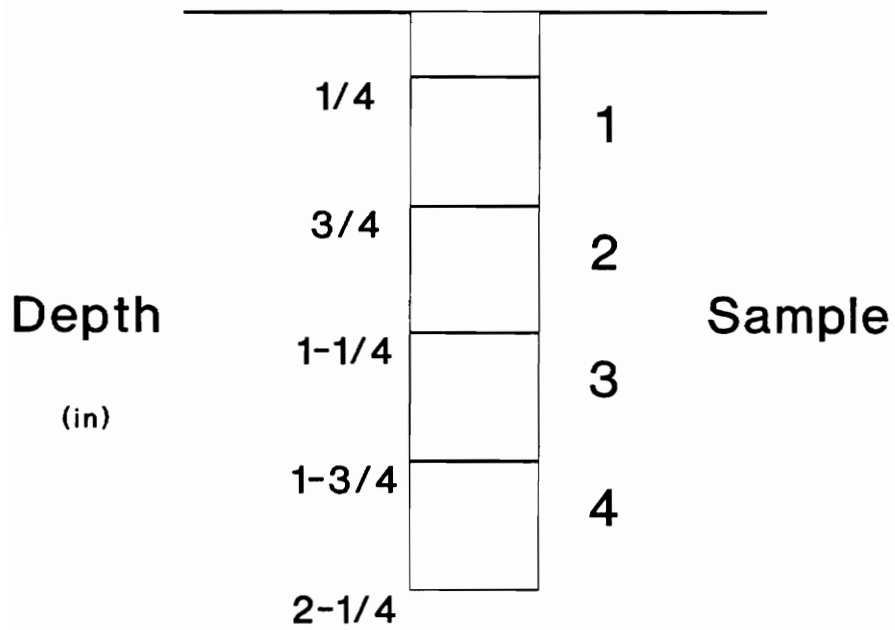


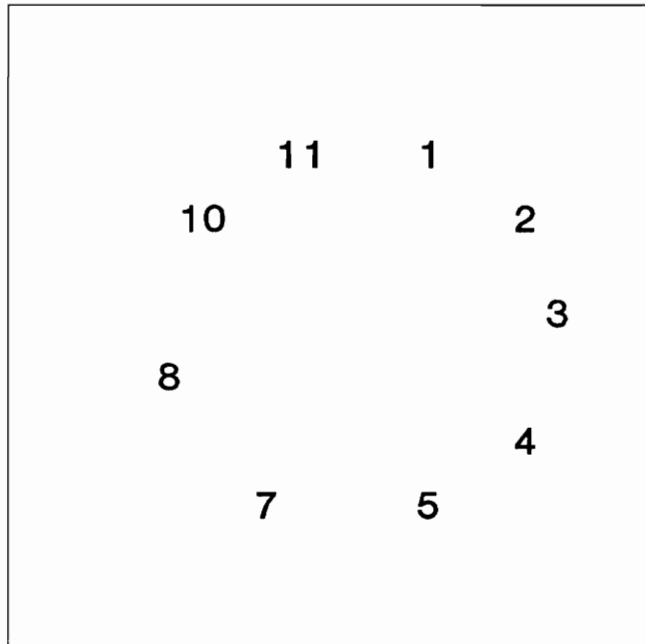
Figure 3.7 Sample Depths for Each Location

slabs, while the vertical specimen samples were taken at varying heights from the back of the wall. The locations were chosen in order not to produce any more destruction of the tested surface than would take place during later sampling.

The sampling schedule involved three measurement intervals after the background tests. Samples were taken after ponding cycles 10, 20, and 30 for the horizontal specimens, and after wetting cycles 11, 21, and 30 for the vertical specimens. Three holes were drilled for each slab, giving a total of 9 samples for any one treatment and depth. Sampling locations on the slab are depicted in Figure 3.8. Each vertical specimen was drilled 5 times at 1-ft (30-cm) intervals along the vertical. Two holes on each section were offset by 2 in. (5 cm) from the center line of the water stream in order to test for possible effects from being on the edge of the wetted area. Figure 3.9 displays the sampling locations for a typical wall section.

3.4.2.2. Chloride Content

Chloride content measurements were performed by two methods. The first, ASTM C-114 [32], was the standard method used for the background samples and a range of other samples. This procedure was done in order to correlate the second method, the rapid chloride determination method developed at Virginia Tech [35], to the accepted standard. Both of these methods measure acid-soluble chlorides using an Ion Sensitive Electrode (ISE). The ASTM method is accomplished through titration, while the rapid chloride determination method measures the millivolt level of the



Locations

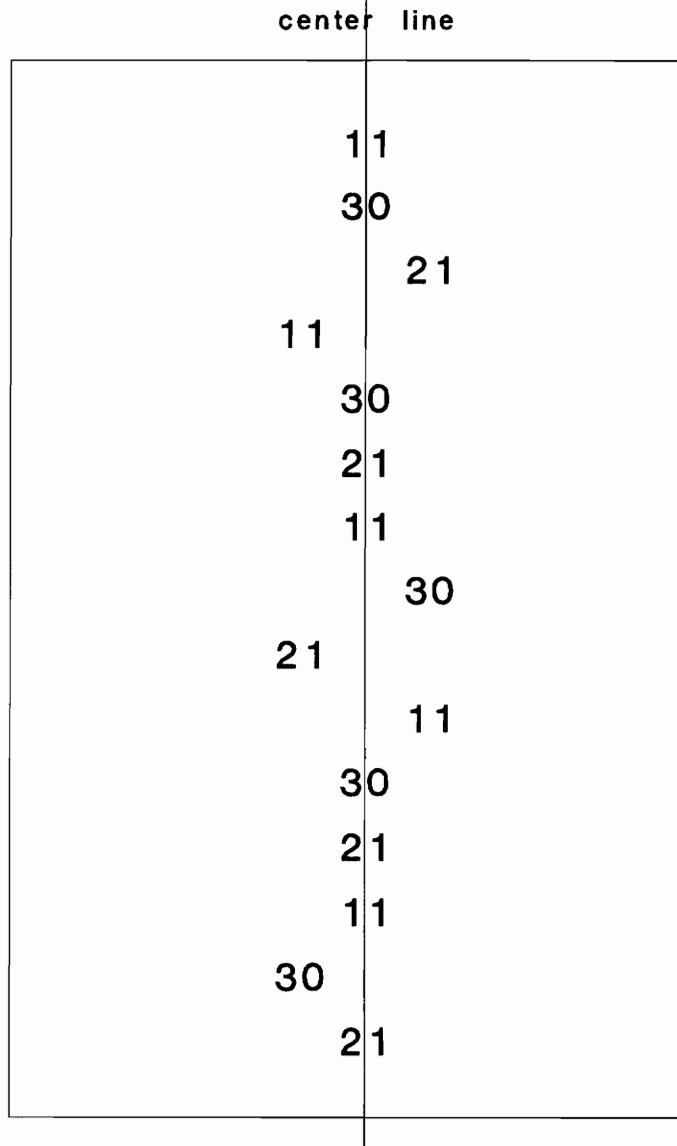
Week 10 - 3,7,11

Week 20 - 1,4,8

Week 30 - 2,5,10

Figure 3.8 Horizontal Specimen Sampling Locations

Typical sampling locations for all specimens
as seen here in W2.



Numbers indicate after which cycle
sample was taken.

Figure 3.9 Vertical Specimen Sampling Locations

digested sample. The rapid chloride determination method was used on the majority of the samples with the transformation to the acid-soluble chloride ion content achieved through calibration to standard solutions followed by calibration to the ASTM method.

3.5. Service Life Prediction

Using the information gathered from chloride content measurements and SAT measurements from all samples, a model was to be developed which would enable the estimation of the service life of the sealers tested. This model would then be able to be used for any sealer tested in a similar manner. Any model should include the influence of the major variables which affect the service life of concrete surface sealers.

4.0.

RESULTS AND DISCUSSION

4.1 Surface Absorption Test

As stated previously, the secondary goal of this research was to explore the possibility of using a Surface Absorption Test (SAT) for a rapid, non-destructive, in-situ determination of the performance of the sealer. The SAT device used was modeled directly after the device produced by Construction Technology Laboratories (CTL) [12]. As described earlier, the timing and number of these tests did not conform to the schedule for various reasons, among them being the inclement weather, difficulties in producing a proper seal between the SAT device and the concrete, and high temperature conditions. The results of the tests taken, along with an analysis of the variables involved follows. Comments on the feasibility of using this device for the intended purpose are also included.

4.1.1. Variation in First Minute

A large number of base measurements were taken (before ponding commenced) in order to familiarize the user with the instrument and technique and to

determine statistical variations between slabs of the same test specimen condition and locations on the same slab. It was noticed during this stage of measurements that a great deal of variation was occurring during the first minute of the 10-minute test time. In Figure 4.1, a plot was made of six measurements taken at the same time period on the control slabs. The curves are quite different in the first minute, but from then until the end of the test time (minute 10), the curves are very similar in slope. To show this more clearly, the same three measurements are plotted in Figure 4.2 with the reading from minute one subtracted from all following readings. It can be seen that the curves are extremely similar in nature. This high variation during the first test minute was found to be common. As shown in Figures 4.3 and 4.4. (for siloxane specimens), this first-minute adjustment can also make identification of outlying measurements an easier task. Therefore, it was decided that in order to compare measurements more accurately, the first test minute measurement would be subtracted and the value reported would then be the column drop from minute one to minute 10 (1-10 min. drop).

4.1.2. Variables Affecting Performance

During base measurements and testing during ponding cycles, a number of variables which affected the test were discovered. Some of these were anticipated, although the extent of the effects were not. Leaks of the seal between the SAT device and the concrete, the moisture level of the concrete surface, and high temperatures,

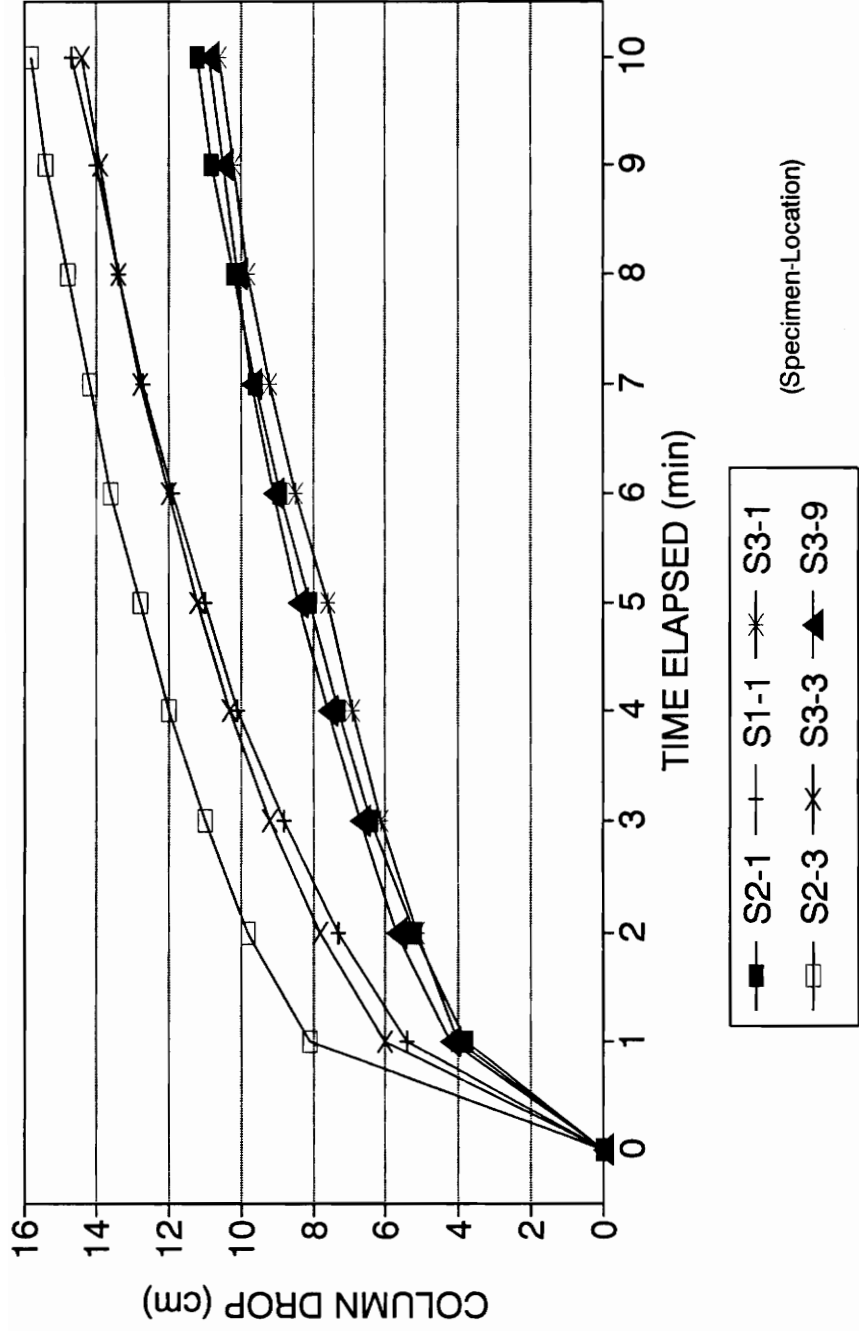


Figure 4.1 Control Specimens: Column Drop from Time = 0 min.

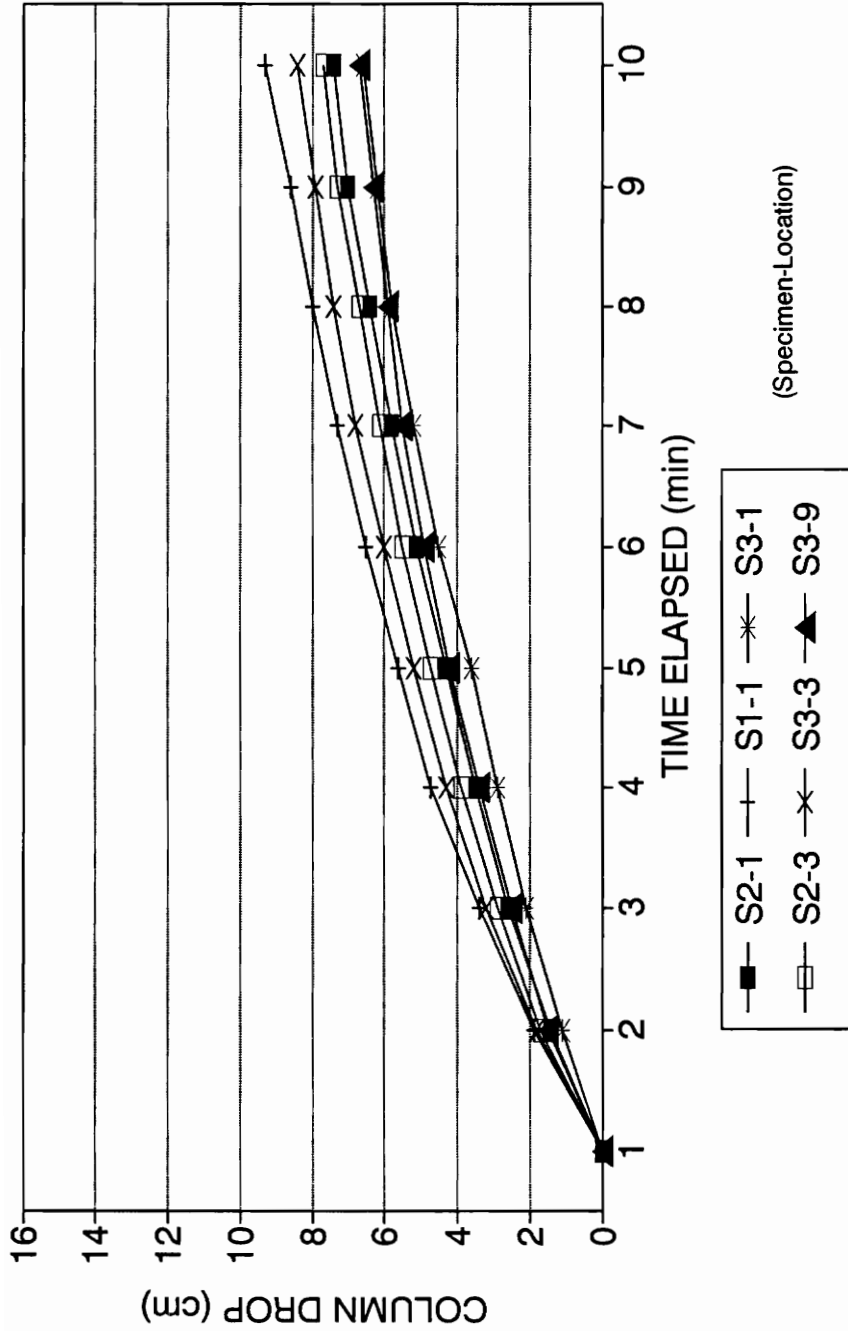


Figure 4.2 Control Specimens: Column Drop from Time = 1 min.

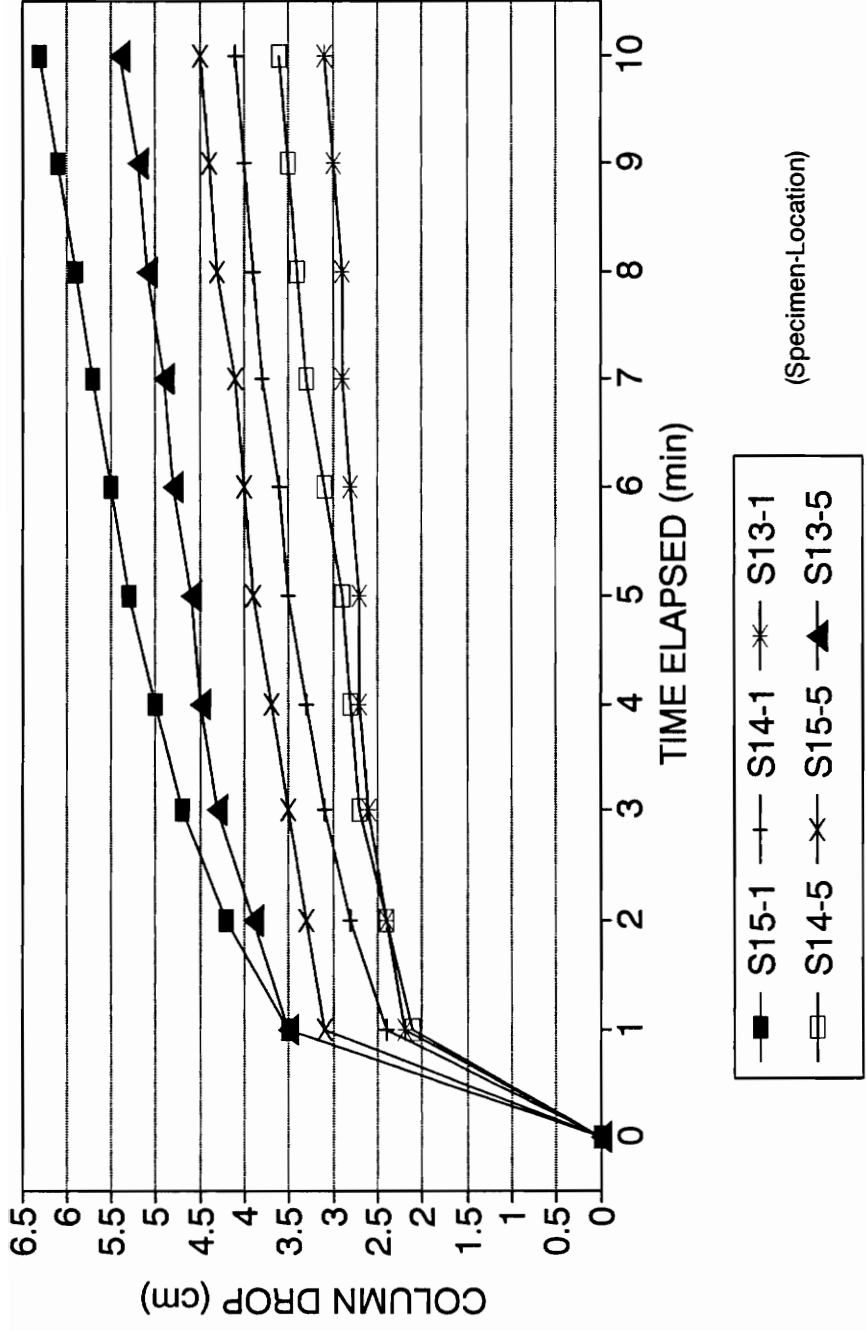


Figure 4.3 Siloxane Specimens: Column Drop from Time = 0 min.

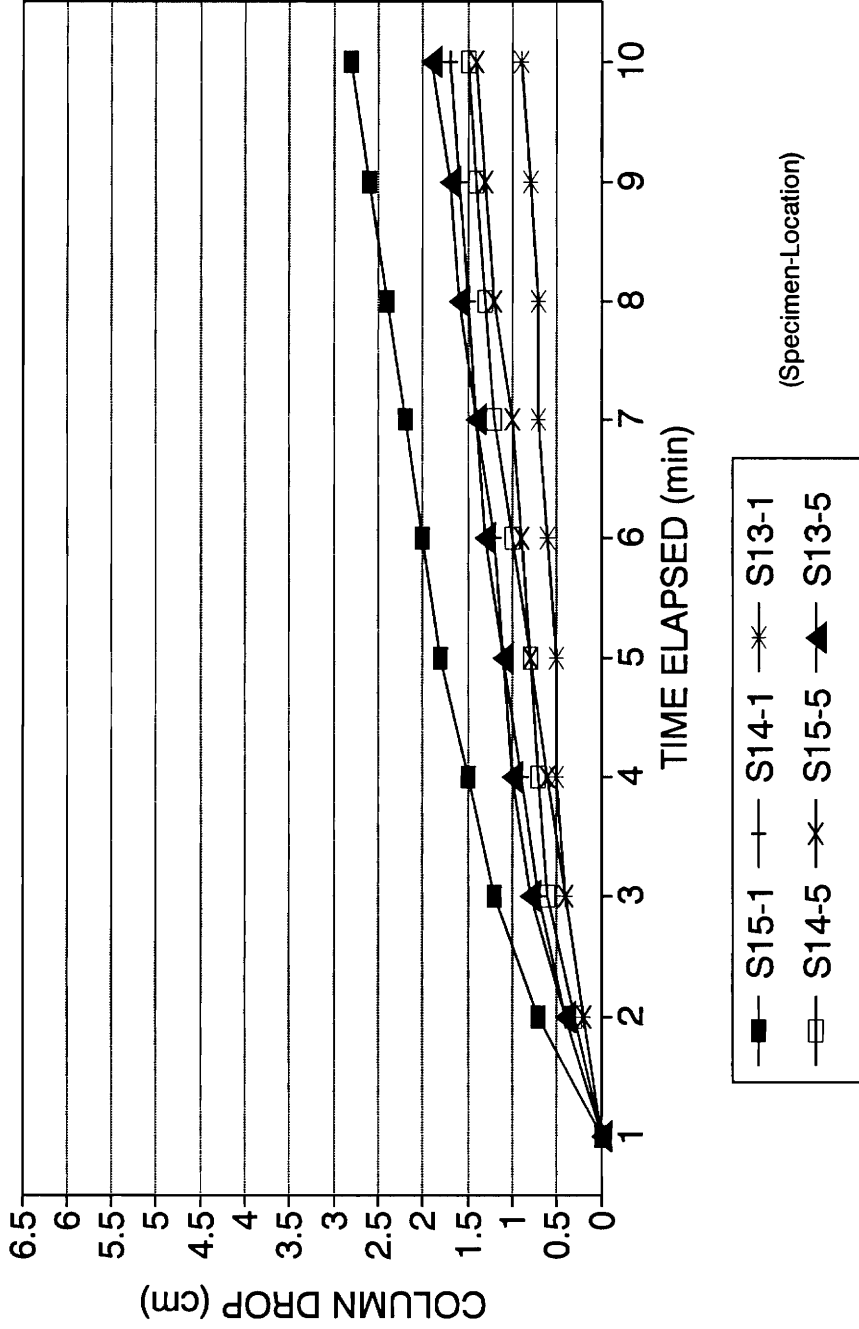


Figure 4.4 Siloxane Specimens: Column Drop from Time = 1 min.

particularly accompanied by direct sunlight, were all major hindrances.

4.1.2.1. Leaks

A leak occurs when water is lost from the chamber of the SAT device through a variety of ways. Obviously, any measurement during which a leak occurred was discarded, but this also meant a loss of data for that location that week. A few leaks occurred at the connection between the upright tube and the chamber. It was discovered that this connection was not threaded and the leaks were stopped by applying silicone caulk.

The greatest difficulty with leaks occurred at the interface between the sealing agent and the concrete. During the first 15 ponding cycles, standard plumber's duct seal was used as a sealing agent. Leaks accounted for 25-35% of all attempted SAT measurements during this time. After the 15th ponding cycle, leaks began to consume over 50% of all measurement attempts. This increase is assumed to be a result of reduced bonding ability between the clay and the concrete surface because of microfractures formed in the concrete during freeze-thaw cycles and/or during drying shrinkage. This was particularly a problem on the control and silane treatments of the vertical specimens, where leaks occurred over 80% of the time. In correlation to this problem, an interesting visual observation was made concerning the wall sections which indicated a difference between the control and silane treatments and the other treatments. During the surface wetting time, the salt water began to trickle down

each section with a stream width about 4 in. (10 cm) wide. On the siloxane and both epoxy sections the width of the stream and associated wetted area remained about 6- to 8-in. (15- to 20-cm) as the water travelled down the section. However, the width of the stream and associated wetted area on the control and silane wall sections was over 20 in. (51 cm). This observation indicated that there was a difference at or near the surface between the two "wide-wetted" sections and the other sections.

A new adhesion material was then used, a combination of clay and grease. A number of attempts to attain a workable mixture of modelling clay and grease, as directed by the SAT literature, failed. Using a different approach, the mixture was heated to approximately 120°F (48°C). This heating produced a homogeneous mixture which allowed it to be rolled out into the proper shapes with ease. Although the leak ratio for the horizontal specimens reduced to 20-25%, the control and silane vertical specimens continued to leak over 80% of the time.

4.1.2.2. Moisture Level

As noted earlier, the moisture level of concrete can cause great differences in the surface absorption characteristics of the concrete surface. This is well depicted in Figures 4.5 and 4.6, which are typical examples. SAT measurements are from the same horizontal slab for each figure, but taken a week apart. The greater absorption occurred on days when the last rain was four or five days previous. The lower readings were taken one day after a significant rain. The temperatures were similar

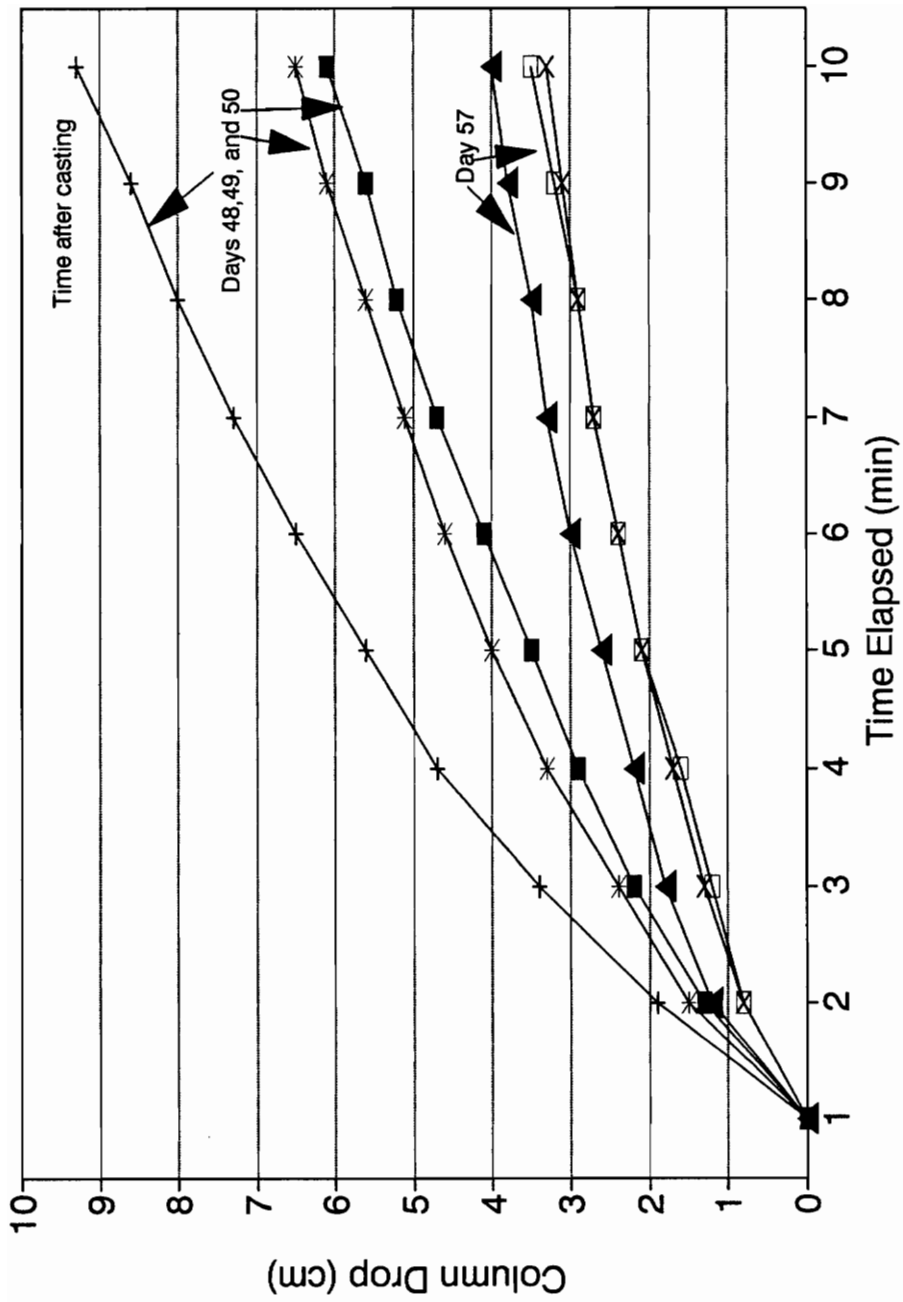


Figure 4.5 SAT Results from Two Time Periods for Control Slab 2

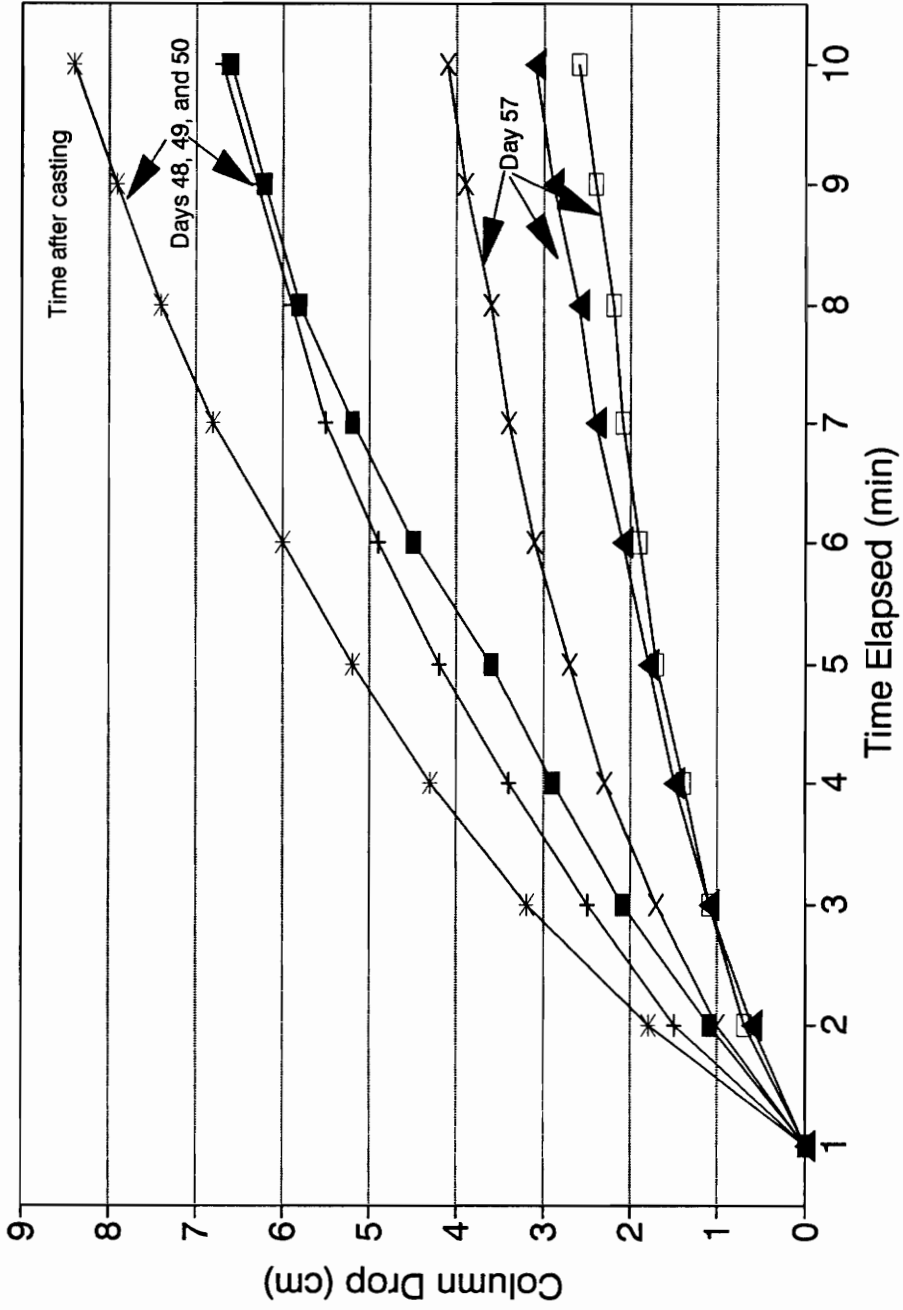


Figure 4.6 SAT Results from Two Time Periods for Control Slab 3

for the two time periods. It is clear that a differences in absorption may be due to moisture level.

It was recommended by the SAT developer [12] that tests either be scheduled for dry periods or that the surface be dried before the measurement is to be taken by subjecting the location to 120°F (48°C) heat for 10 minutes. However, if it does take concrete at least 10 days at 50°C (125°F) to dry to its ultimate SAT measurement, then even readings taken after heating the surface in this manner could not be considered comparable to other measurements taken at varying degrees of moisture content, with or without heating.

At present, the results from both this research and others lead to the conclusion that there is virtually no possibility of comparing SAT measurements of the same treatment from one day to another since there is no assurance that an equal moisture level could be attained. The SAT measurement could very well reflect a change in ambient conditions rather than yield a difference in the quality of the sealer over time [33]. This has also been given as a possible warning by the SAT developer [12].

This would mean that the only possibility of using the SAT measurements as an indication of a sealer's performance would be compare it to the SAT measurements of a control treatment taken the same day. This assumes that the moisture level remains relatively stable for one day.

4.1.2.3. Temperature and Direct Sunlight

The research (by Dhir, Hewlett, and Chan) cited earlier which attempted to shed light on the influence of different variables affecting a surface absorption test was done in the laboratory. In such an environment, the temperature was most likely constant throughout all testing done in one day. Also, no direct sunlight was allowed on the specimens before or during the test. It was found that temperature differences could cause great problems with SAT measurements.

Temperature change of water produces a change in density, and therefore, a set amount of water will either increase or decrease in volume, depending on the temperature differences over that time. The SAT device used in this research had a volume, cell and capillary tube, of approximately 12.2 in³ (200 cm³). The capillary tube itself was 0.125 in (0.3175 cm) in diameter. Therefore, a change of temperature of a few degrees in the water during the test would alter the results significantly. For example, as shown in Table 4.1, a rise in temperature from 70° to 74°F (16.9° to 18.7°C) will lead to an expansion in the water column of 1.04 cm (0.41 in.). This problem was first noted when, on warm days during SAT measurements, the column of water would lose its meniscus and at times even move back up the tube. This problem was mentioned in the report on the SAT by the developer [12]. However, the extent of the problem was not addressed or quantified. In other words, only a warning to keep away from "hot" days was included, and not a detailed description of the differences in readings which could be caused by temperature changes.

**Table 4.1 Change in Column Height Due to Change in Temperature
(water begins at 70°F)**

Temperature Change (degrees F)	Density Change (%)	Column Height Difference (cm)
1	0.01033	0.26
2	0.02066	0.52
3	0.03099	0.78
4	0.04132	1.04
5	0.05165	1.30
6	0.06198	1.57
7	0.07231	1.87
8	0.08264	2.09
9	0.09298	2.35
10	0.10331	2.61

A number of "temperature SAT measurements" were conducted to get an indication of the extent of this problem. These tests were conducted by placing a thermocouple probe into the water cell with temperatures recorded every minute for ten minutes. Measurements were taken in hot (85°F, [23.6°C]) conditions in early afternoon and moderate (75°F, [18.7°C]) conditions in mid-morning. During both times, measurements were taken in direct sunlight and shade conditions. The temperature of the surface had not yet heated during the moderate condition tests, while the concrete was over 100°F (30.2°C) in the hot condition tests. As can be noted from Figure 4.7, only when the temperatures were moderate and in the shade did no appreciable temperature change occur. In any other conditions tested here, a change in the water column height occurred due to temperature change only that would rival the magnitude of the actual absorption property which was attempting to be measured. It is clear that unless the water during SAT measurements is not kept well within a few degrees F over the test time, variations in temperatures would cause comparisons between readings to be futile, even if those measurements were taken the same day (similar moisture conditions). Protection against temperature change during tests needs to be exercised. This could be done by paying strict attention to detail in handling the water and needs to be explicitly spelled out in the SAT procedure literature.

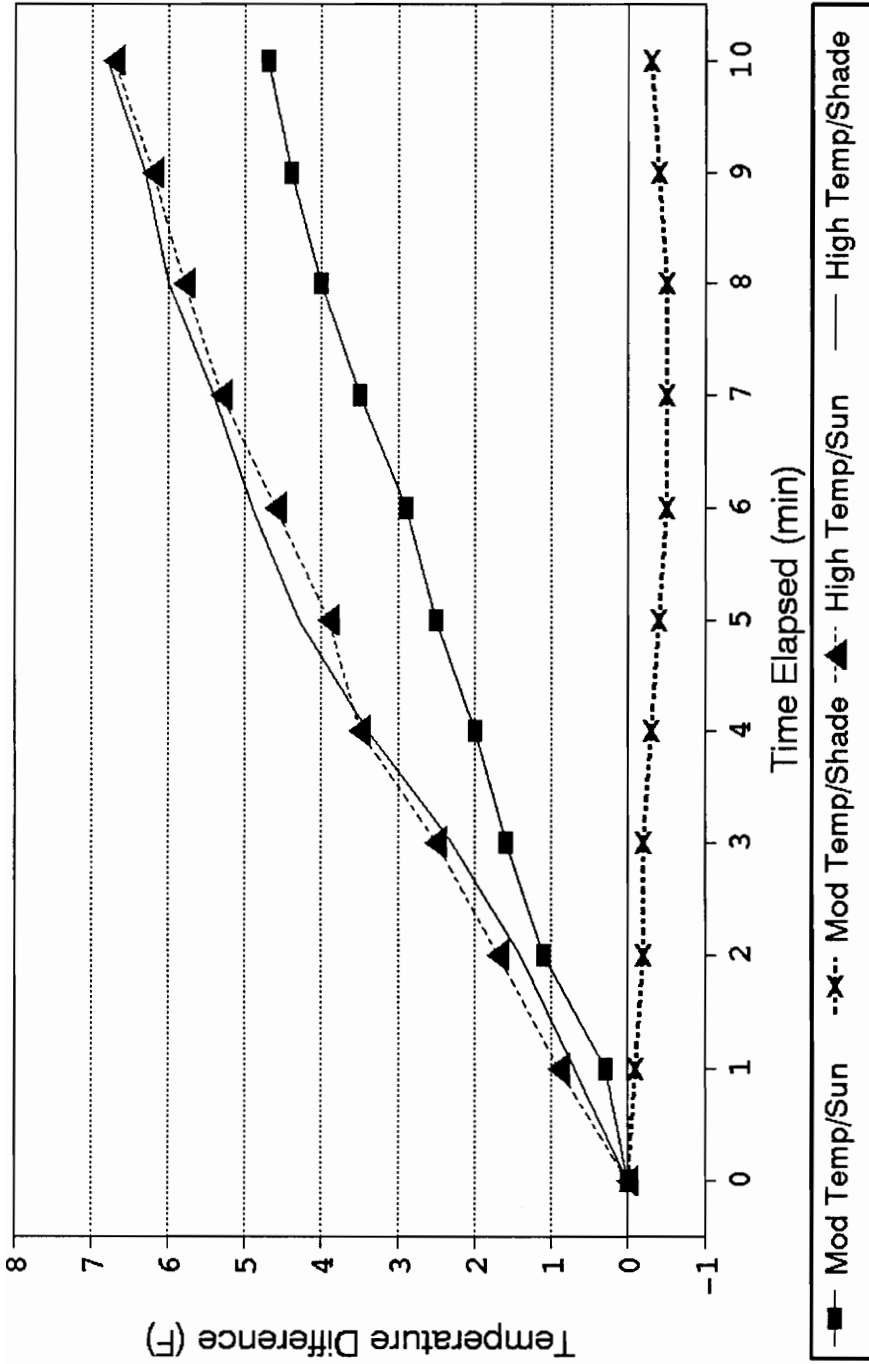


Figure 4.7 Temperature Variation of Water During SAT

4.1.3. Results from Surface Absorption Tests

As discussed above, and as demonstrated below, the only way meaningful results from SAT data can be derived is by comparing treated specimens to control specimens taken the same day.

4.1.3.1. Laboratory Tests

As mentioned, the SAT measurement attempts on the control section of the wall leaked so often as to prevent results from being useful. For this reason, an SAT analysis of the wall was not conducted. The results of the horizontal slabs, however, could be analyzed to some extent. The following discussion deals only with data from the slabs. The results of five days of tests are summarized in Table 4.2. The day number refers to the time from concrete placement. Two of the days were consecutive and represent the base readings. The other three test dates were between ponding cycles. The third and fourth dates included measurements in which the meniscus was lost during the test time. The problem with this analysis can easily be seen in that the average reading for the solvent-based epoxy on the third day is negative. The data from days 158 and 215 are particularly suspect since it is assumed that all the temperature changes were not the same for all tests for each day.

Even then, the results of all the tests were analyzed. In Figure 4.8, the average SAT measurement for the test day was plotted versus time. This did not appear to result in any valuable information which was not surprising considering that

Table 4.2 Summary of Surface Absorption Data for Horizontal Specimens

Date	Days	CONTROL SLABS			WBE SLABS			SBE SLABS					
		Avg from day	Std Dev	Coeff of Var	No of data	Avg from day	Std Dev	Coeff of Var	No of data	Avg from day	Std Dev	Coeff of Var	No of data
11-15	49	7.77	1.387	0.178	3	2.57	0.8622	0.335	3	1.53	0.5508	0.36	3
11-16	50	7.33	0.8884	0.121	4	1.1	0.3162	0.287	4	1.15	0.3209	0.279	6
3-03	158	2.27	1.1015	0.485	3	0.23	0.2517	1.094	3	-0.35	0.4435	-1.267	4
4-29	215	1.6	1	1	1	0.8	0.4243	0.53	2	0.27	0.4041	1.497	3
7-14	292	1.85	0.3536	0.191	2	1.4	1	1	1	2	0.1414	0.071	2

Date	Days	SILANE SLABS			SILOXANE SLABS				
		Avg from day	Std Dev	Coeff of Var	No of data	Avg from day	Std Dev	Coeff of Var	No of data
11-15	49	1.8	0.4637	0.258	5	1.48	0.3768	0.255	5
11-16	50	0.87	0.0577	0.066	3	0.57	0.3786	0.664	3
3-03	158	1	1.2124	1.212	3	0.67	0.288675	0.431	3
4-29	215	0.15	0.2121	1.414	2				
7-14	292	1.43	0.2082	0.146	3	0.97	0.0577	0.06	3

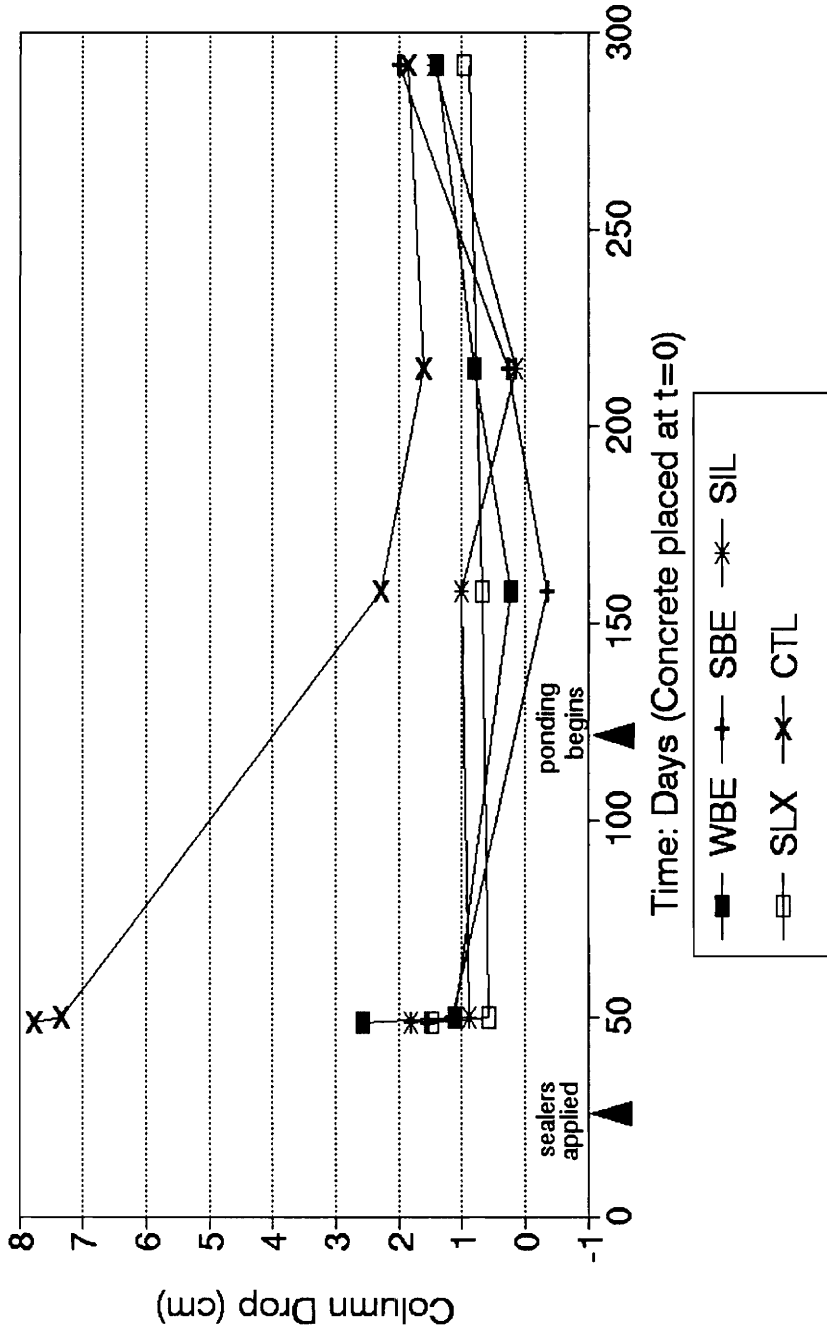


Figure 4.8 Average SAT Measurements for Sealed and Control

the readings were conducted without assurance of constant surface moisture level.

Therefore, it was obvious that a comparison to the control section would be the only way to judge the effectiveness of the sealer. At first, the difference between the sealed and control slabs was examined. Figure 4.9 shows the result of this analysis. It also did not appear to yield useful information. This is not surprising since differences in surface absorption during high-moisture-condition days would be expected to be greater than differences on low-moisture-days. The control specimens have much more latitude for variations between these two conditions.

The next approach in analyzing the SAT data was to look at the fraction of the sealed specimens over the control. This method of comparing treatments by looking at ratios of sealed-to-unsealed specimens was used in Whiting's analysis of the "Rapid Determination of the Chloride Permeability of Concrete" [27]. Figure 4.10 shows the results of this approach. Even with the highly suspect two days, an upward trend can be perceived, indicating a move toward unsealed status of the sealed specimens. This is what would be expected as the sealers decay. One difficulty which may cause problems occurs when all measurements, including the control, yield small water column drops, as would be expected during low-moisture days. The technique may not be sensitive enough to be able to discern between treatments.

It should also be noted that research has shown that sorptivity test results are somewhat dependant on the temperature of the liquid being used [36]. Since surface absorption works under the same capillary mechanism, it must be the case that surface

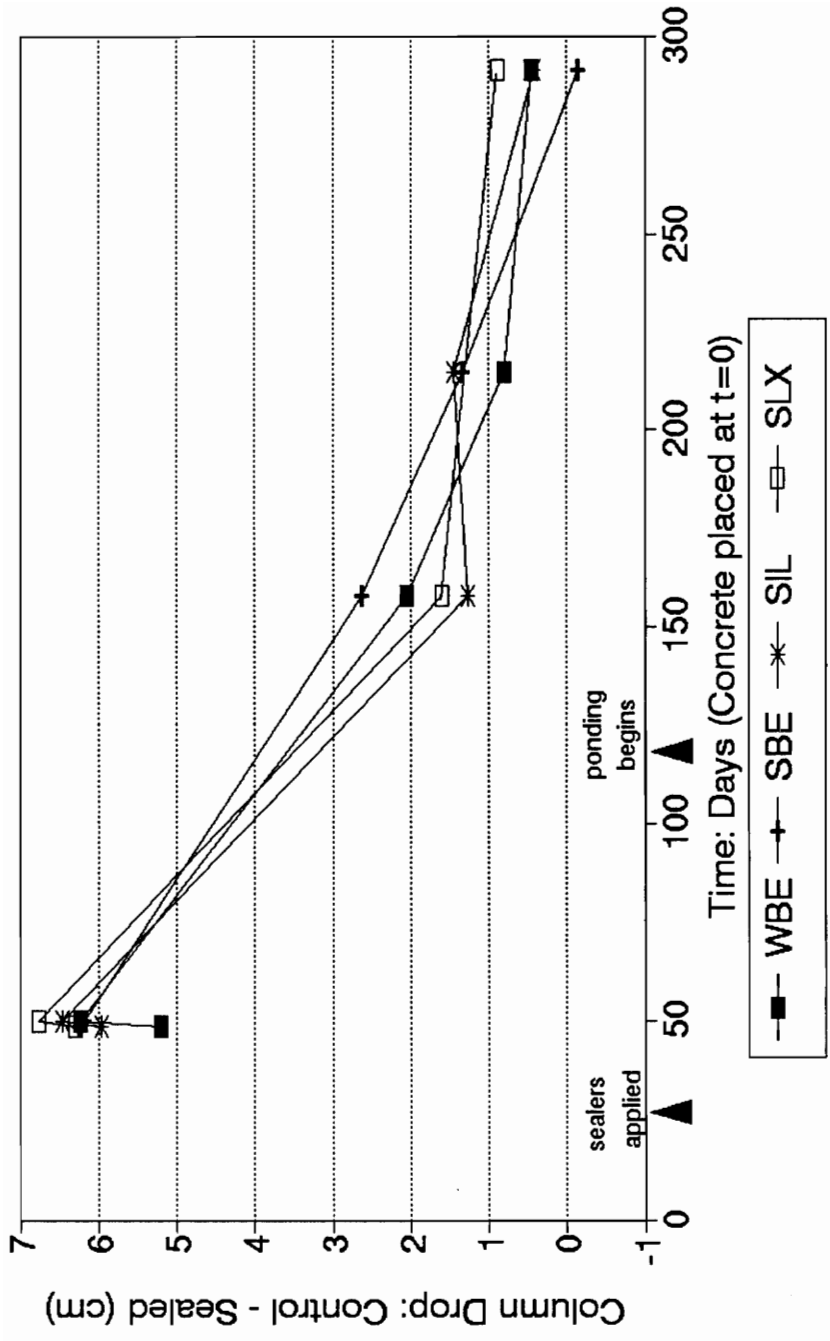


Figure 4.9 Differences in SAT Measurements: Control - Sealed

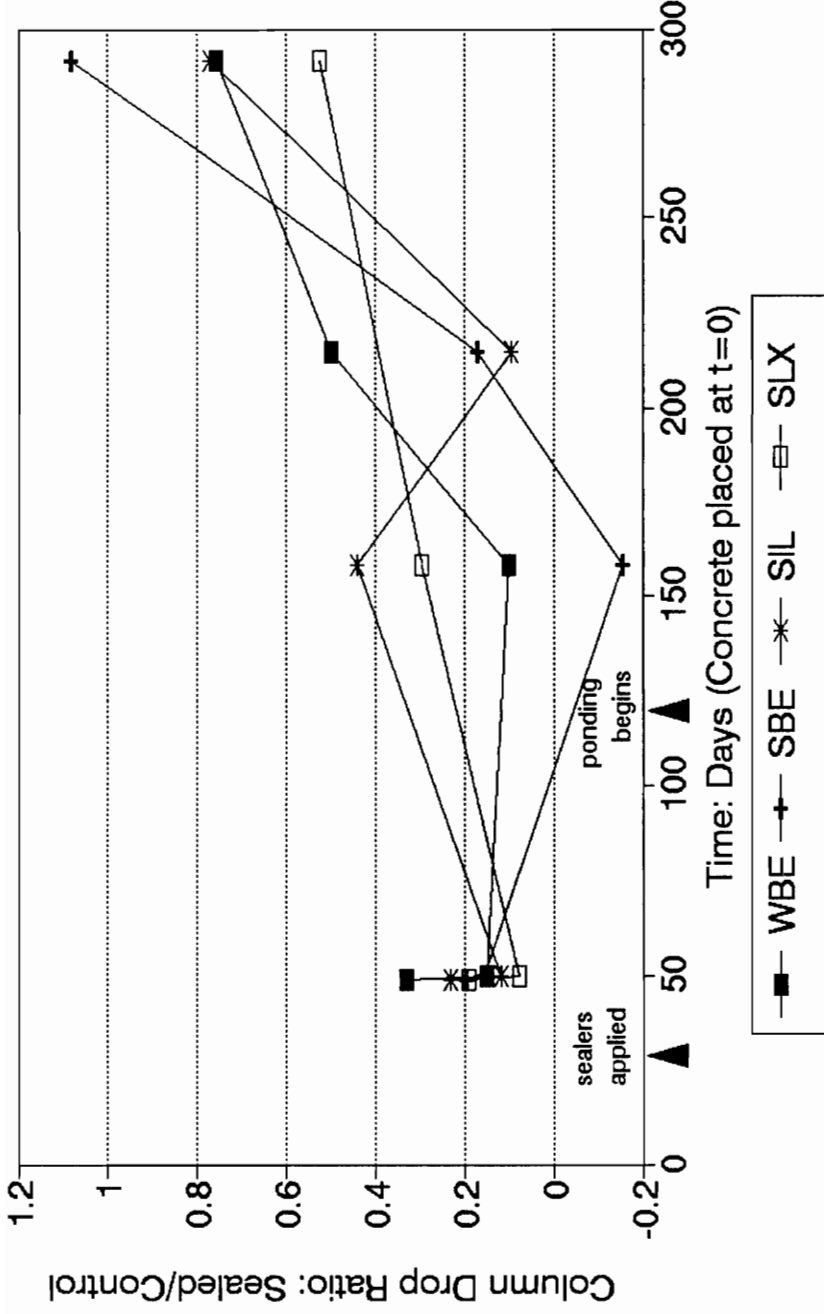


Figure 4.10 Ratio of SAT Measurements: Sealed/Control

absorption is also dependant on the temperature of the liquid [36]. It has been demonstrated, theoretically and empirically, that a difference in water temperature from 50°F (10°C) to 68°F (20°C) would result in a 13% increase in the surface tension/viscosity $[(\sigma/\eta)^{1/2}]$ factor. Since this is directly proportional to the sorptivity which is directly proportional to absorption [36], the SAT measurement would vary by the same proportion. Adjustments for water temperature were not discussed in the SAT procedure literature at all, but should be considered in any more detailed analysis of this test.

4.1.3.2. Guidelines and Correlation

It is clear that the difficulties encountered during the testing period of this research will cause any future testing to be restricted by certain guidelines. These guidelines should include the following: SAT measurements should be taken after at least four precipitation-free days; no direct sunlight should be permitted on the SAT device during measurement; measurements should be taken when concrete surface and water reservoir temperature differential is less than 4°F (1.5°C); and solar heating of the concrete surface should be avoided before measurements by covering the area. These steps constitute a reasonable beginning toward a set of criteria which is absolutely necessary if surface absorption is to be used for any fruitful data collection. The first requirement of a 4-day drying period minimum, is a compromise between a more restrictive regulation argued for by the moisture data and the reasonable

probability of precipitation-free days. The temperature differential guideline could possibly be placed lower, but it is assumed that the cell water will not heat up (or cool down) by the entire differential. As for the fourth guideline, this can be accomplished by using a large sheet of white plastic placed above the measurement location.

In an attempt to correlate the SAT data to chloride ingress, the SAT results from the final series is compared to the increase in chlorides after 30 ponding cycles at the first two depths. This comparison is shown in Table 4.3. It is noted that the SAT roughly ranked the treatments in the same order of effectiveness that the chloride analysis did for both depths, that being, from worst to best, CTL-SBE-WBE-SIL-SLX. But serious differences occur when analyzing the magnitude of these differences. Although the solvent-based epoxy was ranked equal or slightly better in effectiveness than the control by the chloride data, it was ranked slightly worse by the SAT data. The water-based epoxy was ranked with ratios of about 80-90% of the control by both the chloride and SAT data. But when examining the silane treatment, the SAT information ranked this about equal with the water-based epoxy, while the chloride data clearly indicates that the silane performed at a far better level, approximately the level of the siloxane treatment. Along with this, even though the siloxane (and silane) prevented over 90% of chlorides from entering, the magnitude indicated by SAT testing was far less.

In considering that only the first and last SAT measurements can be considered

Table 4.3 Comparison of SAT Results to Chloride Ingress Data from Week 30 for Horizontal Specimens

Treatment	Cl Ingress and Ratio: Week 30 - Depth 1		Cl Ingress and Ratio: Week 30 - Depth 2		SAT Ratios Week 30
	Ingress (lb/yd ³)	Ratio (/CTL)	Ingress (lb/yd ³)	Ratio (/CTL)	Treatment /Control
CTL	6.93	1.00	1.07	1.00	1.00
SBE	6.87	0.99	0.97	0.91	1.08
WBE	6.39	0.92	0.89	0.83	0.76
SIL	0.10	0.01	0.06	0.06	0.77
SLX	0.05	0.01	0.08	0.07	0.52

somewhat reliable due to ambient condition difficulties, a general trend of sealer decay and treatment differences is noticed. But when the difficulty in magnitude as described above is considered, a very general ranking in categories such as excellent, good, and poor, is the only option which may be available in SAT interpretation. For the purposes of this study, the SAT is used in a very general way, and even then, only in conjunction with visual observation and logical reasoning.

4.1.3.3. Field Tests

Surface Absorption Tests were planned for the field specimens. Base measurements were taken only on the control section of each bridge. This was done in order to get a general condition status of the untreated surface and with the assumption that the initial SAT measurements in the field would be roughly equivalent to the initial measurements on the horizontal laboratory specimens. The field specimens were revisited for SAT measurements one time during the laboratory sampling schedule. These data were not conclusive since the difficulties with moisture and sunlight, which were not fully identified until well into the testing phase, interfered with the results.

The bridges were visited at the end of the research period and SAT measurements were conducted using the guidelines explained previously. The Interstate 81 bridge was tested approximately nine months after sealer application. Two regions of each section were tested, the shoulder and the wheel path. Three

SAT's were taken in each of these regions for each section, and the results are presented in Table 4.4. It can be noted that the ratios of the sealed to unsealed sections were never lower than 64%. For all the sealers the wheel path ratio was higher than the shoulder, which is to be expected due to the effect of traffic wear.

The Pepper's Ferry bridge was visited the day after the Interstate 81 bridge. SAT measurements on this bridge surface were not complete before a rain shower ended the measurement time. It was also not clear whether widely scattered showers the day before fell or had not fallen on this bridge. Therefore, the data was processed, but the bridge was revisited 11 days later, 4 full days after rain in the region. At this time, a full day's readings were taken. The results are shown in Table 4.4. The odd aspect of these results is that, although the shoulder readings were what was expected of the control versus the sealed sections, the wheel path regions yielded highly questionable data with the sealed sections performing worse than the control. It is possible that the tyned surface somehow interfered with normal results either in the sealer application or in SAT testing.

It is necessary to analyze the field SAT data in light of the laboratory SAT data since the lab data was the only connection to chloride ingress. With this in mind, Table 4.5 displays the treatment/control ratios of the laboratory and shoulder data from the field. The SAT data from the bridge decks were chosen for comparison since they experienced the same general conditions as the laboratory specimens, namely, minimal traffic wear and exposure to ultraviolet radiation. From this

Table 4.4 Surface Absorption Test Results for Bridges

I-81 over 611										
	CTL		WBE		SBE		SIL		SLX	
	Average	COV	Average	COV	Average	COV	Average	COV	Average	COV
Wheel Path	1.5	0.13	1.33	0.38	1.1	0.4	1.63	0.2	1.27	0.09
Shoulder	1.3	0.27	1.03	0.34	0.83	0.07	1.3	0.47	0.9	0.4
Ratio: Sealed/Unsealed										
Wheel Path			0.89		0.73		1.09		0.85	
Shoulder			0.79		0.64		1		0.69	
Pepper's Ferry Bridge over New River										
	CTL		WBE		SBE		SIL		SLX	
	Average	COV	Average	COV	Average	COV	Average	COV	Average	COV
Wheel Path	1.03	0.15	1.47	0.22	1.17	0.41	1.47	0.55	0.9	0.22
Shoulder	1.4	0.38	1.3	0.31	1.13	0.36	1.1	----	0.83	0.14
Ratio: Sealed/Unsealed										
Wheel Path			1.43		1.14		1.43		0.87	
Shoulder			0.93		0.81		0.79		0.59	

Table 4.5 Comparison of SAT Treatment/Control Ratios from Laboratory and Bridge Deck Shoulders

Treatment	Laboratory Slabs (Week 30 - Depth 1)	I-81 Bridge (9 months)	Pepper's Ferry Bridge (9 months)
CTL	1.00	1.00	1.00
SBE	1.08	0.64	0.81
WBE	0.76	0.79	0.93
SIL	0.77	1.00	0.79
SLX	0.52	0.69	0.59

comparison, the relative rankings resulting from each specimen type should be noted. The laboratory specimens yield $SBE > CTL > WBE = SIL >> SLX$ in terms of ratios (note that this is opposite of effectiveness). The I-81 bridge ranks the treatments $CTL = SIL > WBE > SLX = SBE$, while the Pepper's Ferry Bridge ranks them $CTL > WBE > SBE = SIL >> SLX$. The $>>$ indicates a greater increase in magnitude of effectiveness than the $>$ sign. Two treatments are considered equal ($=$) if their ratios are within 5%. Before comments can be made regarding the differences in rank, it must be noted that the relatively low number of measurements and high coefficient of variations (averaging 0.29 for the bridges) would mean that the results are in need of verification through more comprehensive tests.

The best correlation between the specimen types is that the siloxane treatment consistently had the lowest ratio, which is consistent with the fact that its performance in the chloride ingress testing was excellent. However, the variation in the ranking between the three surfaces is significant. The I-81 bridge ranked the solvent-based epoxy on par with the siloxane, while the other bridge ranked it with the silane, a little worse than the water-based epoxy. The laboratory slabs place the SBE worse than the control. The silane treatment also moved significantly between rankings, being in the middle on the Pepper's Ferry bridge and slabs, but as bad as the control on the I-81 bridge. That measurement set did have the highest coefficient (0.47) of variation of any other.

The great differences in ranking leads one to one of two possible conclusions.

First, the sealers tested could perform at different levels after being applied to different substrates. This is supported by the fact that, as mentioned earlier, the characteristics of the substrate, along with ambient conditions at the time of application, influence the performance of the sealer. It should also be mentioned that the three surfaces were quite different in age and texture.

Secondly, the SAT may rank sealers differently on different surfaces even if they were performing at the same level. As the laboratory specimens indicated different performance between SAT and chloride ingress, it may also be the case that the influences on the SAT, especially considering the variation in surface textures, cause the rankings to differ. Also it should be remembered that the SAT comparison with chloride results in the horizontal specimens were misleading, particularly in magnitude. If the SAT device performed that differently in the field when attempting to measure sealer performance, the results are suspect.

Again, it is pointed out that the lack of comprehensive data and low coefficients of variation prevent firm conclusions. But it can be emphasized that, even though there exist difficulties with data and rankings, every ratio for each treatment is greater in the wheel path than on the shoulder. This indicates that traffic wear, in all likelihood, does have some effect on service life, possibly even with the penetrants.

4.2 Chloride Ion Measurements of Laboratory Samples

The chloride ion profiles were plotted for the laboratory specimens over time. As described in chapter 3, concrete samples were collected from the slabs before ponding and after cycles 10, 20, and 30. For the wall, concrete samples were taken before surface wetting and after cycles 11, 21, and 30. For all but the background measurements, four depths were sampled for analysis.

4.2.1. Background Chloride Content

The background chloride content was measured in order to determine how much chlorides diffused into the concrete due to ponding. ASTM C-114 [32] was used in all background calculations in order to accurately determine this level. The ASTM test method was also used in order to determine the correlation of the background level to the rapid chloride determination method. Since most of the measurements were done with the rapid method, a well-established background correlation seemed appropriate. From 9 samples which were analyzed, the average background chloride was found to be 0.54 lb/yd³ (2.32 kg/m³) of concrete. The coefficient of variation for all 9 observations was 0.14. A summary of the background chloride content determination is displayed in Table B1.

4.2.2. Calibration of Rapid Chloride Determination Method

The first two sets of samples (weeks 10-11 and 20-21) were analyzed during

the same time period. As the rapid method indicates, a calibration of the probe was performed before any readings were taken. However, due to drifts in the probe from one day to the next, this initial probe calibration to the standard solutions could not be used for readings during following days in the laboratory. Indeed, a number of calibration sets (10 measurements of five standard solutions) yielded slightly different results in terms of the linear regression coefficients. The probe was continually checked before and during each day of readings. It was decided that for an accurate determination of the true calibration of the probe, these readings from the measurement days would be used. Of all the chloride measurements performed before and during the analysis day, two calibration conditions of the probe were discovered. In other words, the millivolt values from the ISE probe in the rapid method could be divided into two groups, each group yielding slightly different regression coefficients. The results of the two calibration regressions are found in Tables 4.6a and 4.6b, and plotted in Figures 4.11 and 4.12. It should be noted that the regression coefficients do not differ greatly, but the difference can be noted in later calculations.

Week 30 measurements were done at a different time than the first two series. With the drift of the probe in question, a predetermined approach to the probe calibration was planned. Three sets of calibration solution checks were done before beginning measurements for the day, and after every two groups of measurements. A group of measurements consisted of 15 or 12 samples, depending on whether slab or

Table 4.6a ISE Probe Calibration for Calibration Condition 1		Table 4.6b ISE Probe Calibration for Calibration Condition 2		Table 4.6c ISE Probe Calibration for Calibration Condition 3	
Average Millivolts	ppm of Calibration Solution	Average Millivolts	ppm of Calibration Solution	Average Millivolts	ppm of Calibration Solution
127.29	3	128.2	3	128.2	3
102.56	9	104.85	9	104.85	9
46.56	90	49.53	90	49.53	90
29.55	180	32.46	180	32.46	180
11.73	375	14.86	375	14.86	375
log(ppm)		log(ppm)		log(ppm)	
	0.477		0.477		0.477
	0.954		0.954		0.954
	1.954		1.954		1.954
	2.255		2.255		2.255
	2.574		2.574		2.574
Regression Output:		Regression Output:		Regression Output:	
Constant	2.789898	Constant	2.854405	Constant	2.849034
Std Err of Y Est	0.026102	Std Err of Y Est	0.027356	Std Err of Y Est	0.031671
R Squared	0.998953	R Squared	0.99885	R Squared	0.998464
No. of Observations	80	No. of Observations	80	No. of Observations	70
Degrees of Freedom	78	Degrees of Freedom	78	Degrees of Freedom	68
X Coefficient(s)	-0.01805	X Coefficient(s)	-0.01836	X Coefficient(s)	-0.01886
Std Err of Coef.	6.62E-05	Std Err of Coef.	7.06E-05	Std Err of Coef.	8.97E-05

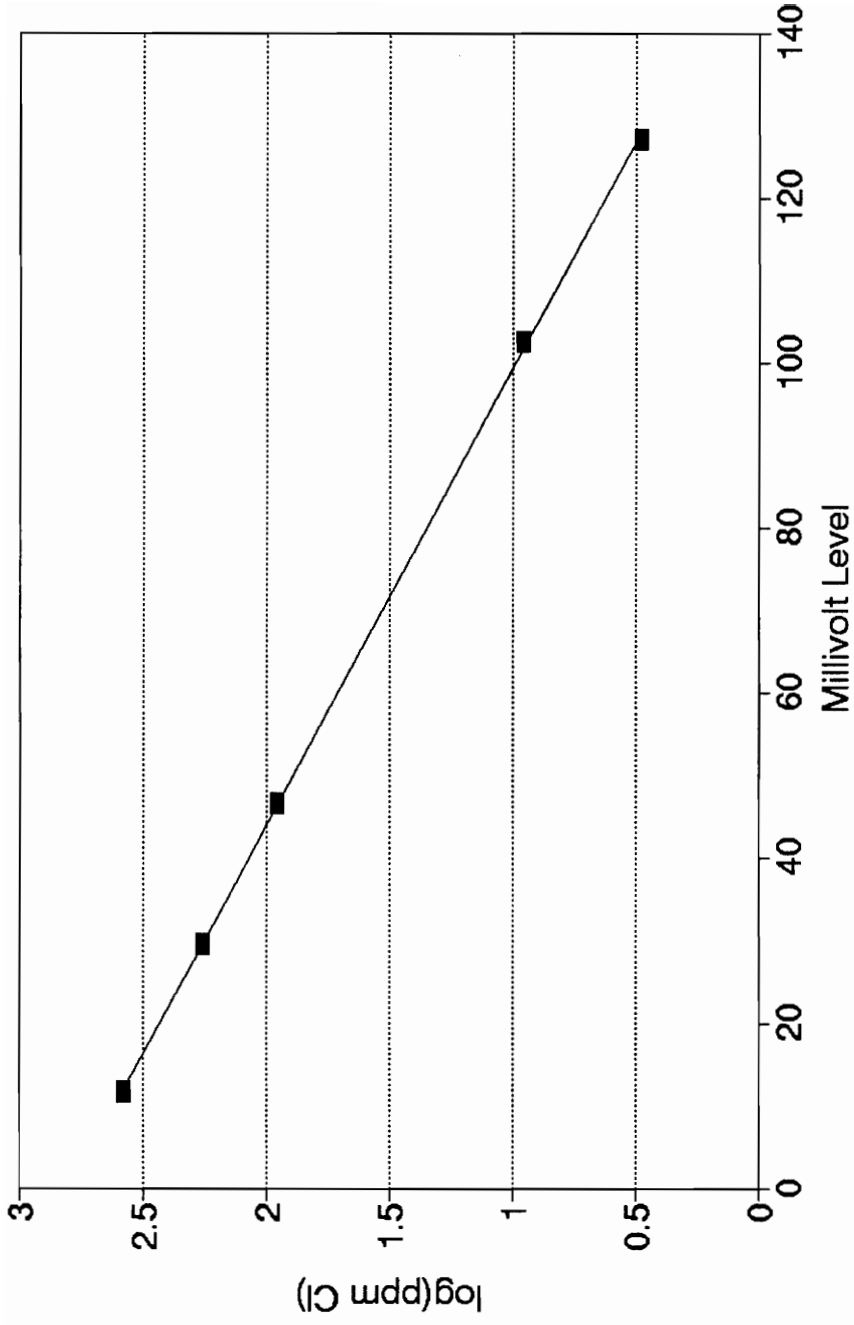


Figure 4.11 ISE Probe Calibration for Rapid Method (Calibration Condition 1)

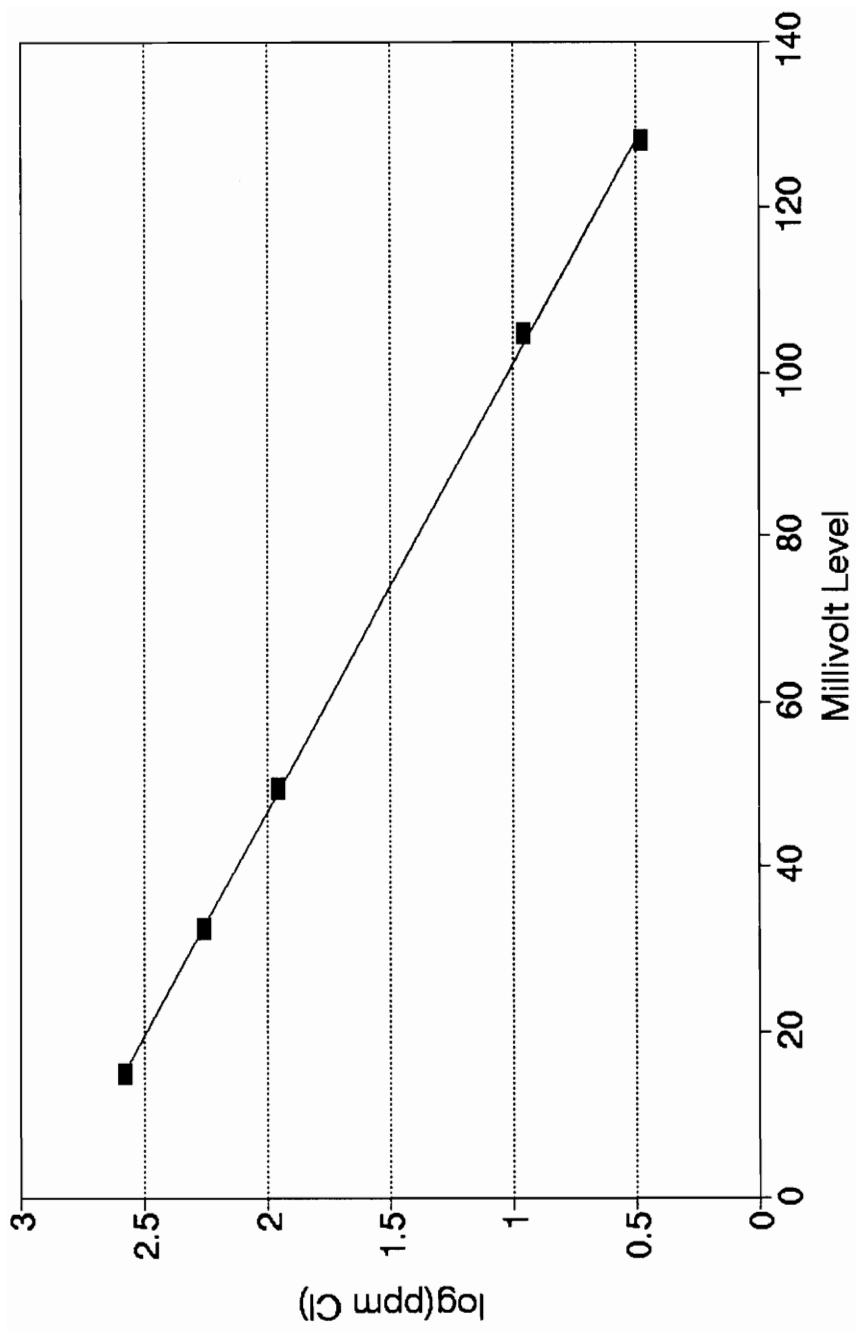


Figure 4.12 ISE Probe Calibration for Rapid Method (Calibration Condition 2)

wall samples were being tested. In the place of the 10 runs of the calibration solutions, the data from the daily and bi-grouply runs were used in the calibration of the ISE probe for the probe condition during all week 30 measurements. This calibration regression for is shown in Table 4.6c and plotted in Figure 4.13.

4.2.3. Rapid Method Correlation to ASTM Method

According to the rapid chloride determination method, after the ISE probe is calibrated, the values must then be correlated to the ASTM standard through linear regression. This was done by choosing 12 samples which represented an even distribution over the range of the chloride measurements from the first two sampling times (cycles 10-11, and 20-21). The results of this correlation are seen in Table 4.7 and graphed in Figure 4.14.

Even though there were three different calibration conditions for the ISE probe, only the second condition, represented in Table 4.6b, was used in the correlation to the ASTM standard. This was done because the probe for the rapid method was in calibration condition 2 when the correlation was done. In order to achieve accurate results for the samples analyzed while the probe was in the other two calibration conditions, the values from those days were first transformed via simple linear regression into condition 2 readings. This added another linear regression which needed to be performed on those values, but in order to retain the proper interpretation of the data obtained, this was necessary. An analysis of the effect of

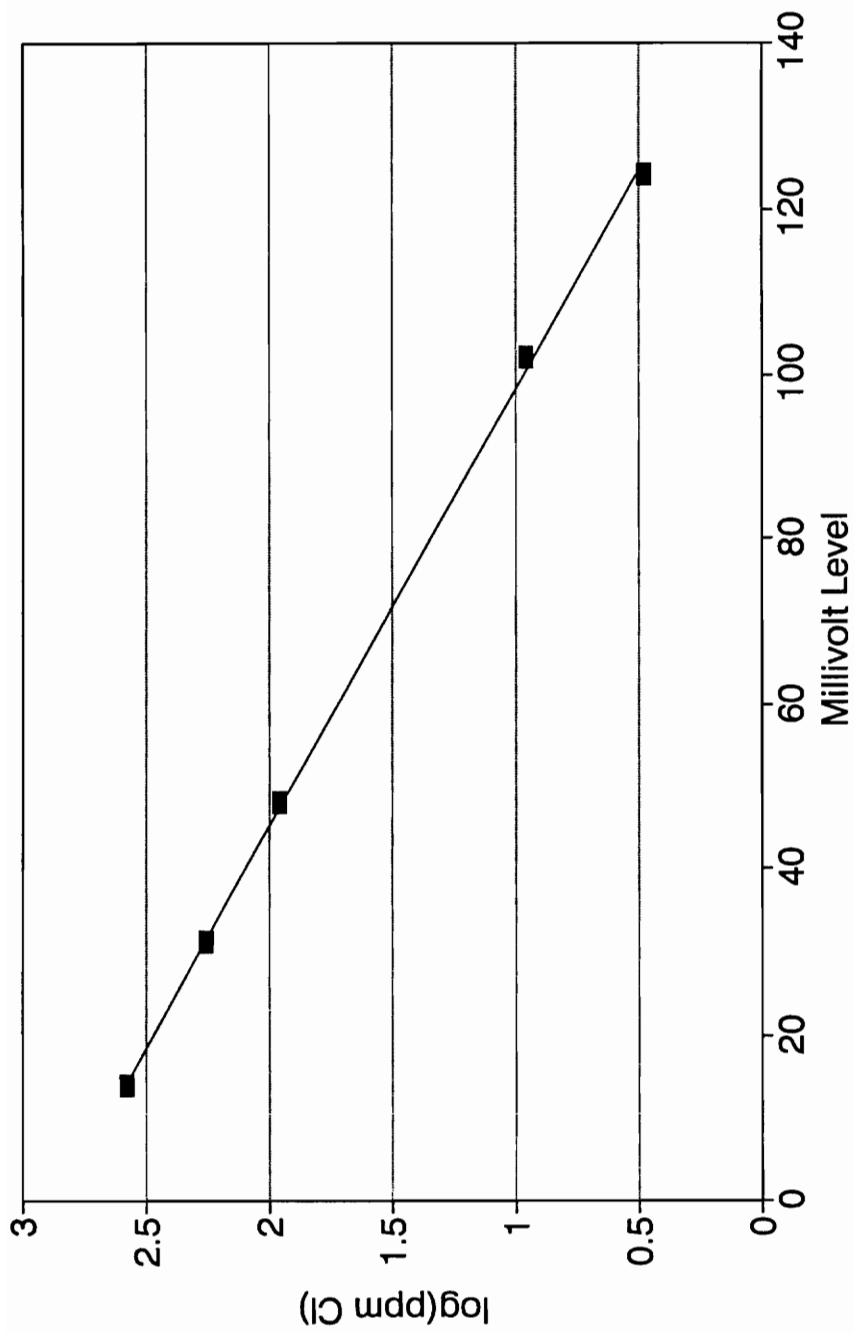


Figure 4.13 ISE Probe Calibration for Rapid Method (Calibration Condition 3)

**Table 4.7 Correlation of Rapid Method
to ASTM Method**

Sample	%CI Calculated	
	VPI %CI	ASTM %CI
S9-20-8-1	0.00462	0.019499
S3-20-4-1	0.00852	0.020208
S8-20-1-1	0.01927	0.035453
S4-20-1-1	0.01729	0.040594
S7-20-8-1	0.02618	0.043253
S9-20-4-1	0.03954	0.062929
S8-10-7-1	0.05094	0.069842
W2-11-1-2	0.05228	0.076756
W1-11-5-2	0.07699	0.1115
S5-10-11-1	0.09022	0.123908
W1-11-3-2	0.10743	0.14128
S5-20-4-2	0.11496	0.15103

Regression Output:

Constant	0.0135128
Std Err of Y Est	0.0034646
R Squared	0.9949797
No. of Observations	12
Degrees of Freedom	10
X Coefficient(s)	1.207378
Std Err of Coef.	0.027121

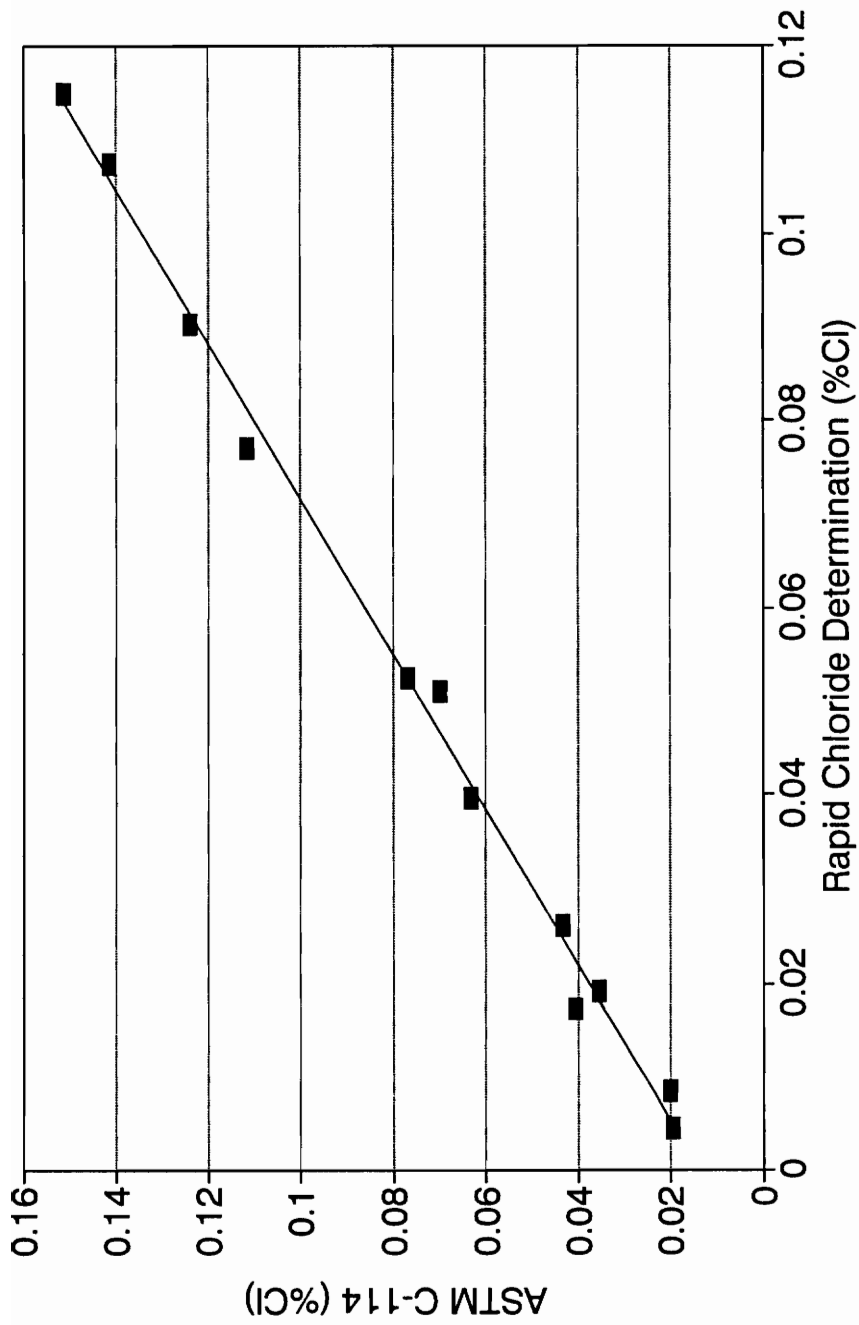


Figure 4.14 Correlation of Rapid Method to ASTM C-114

Table 4.8 Comparison of Average Chloride Analysis Data for Control, Water-Based Epoxy, and Silane Treatments: Including Added Linear Regression Due to ISE Probe Condition Change vs. Excluding Added Linear Regression

Sample Spec-Wk-Depth	Probe Condition	Including Added Linear Regression			Excluding Added Linear Regression		
		AVG	STD	COV	AVG	STD	COV
CTL-10-1	1	2.33	0.695	0.298	2.68	0.780	0.291
CTL-10-2	1	0.68	0.160	0.236	0.83	0.179	0.215
CTL-10-3	1	0.49	0.100	0.204	0.62	0.111	0.180
CTL-20-1	1	4.10	0.951	0.232	4.67	1.070	0.230
CTL-20-2	1	0.61	0.167	0.275	0.76	0.187	0.246
CTL-20-3	2	0.48	0.036	0.075	----	-----	-----
CTL-30-1	3	7.32	1.550	0.211	7.98	1.620	0.204
CTL-30-2	3	1.46	0.471	0.322	1.73	0.512	0.296
CTL-30-3	3	0.37	0.031	0.084	0.53	0.034	0.065
WBE-10-1	1	1.62	0.442	0.273	1.88	0.495	0.263
WBE-10-2	1	0.66	0.116	0.175	0.81	0.129	0.159
WBE-10-3	1	0.50	0.069	0.138	0.63	0.077	0.122
WBE-20-1	1	3.19	0.447	0.140	3.65	0.503	0.138
WBE-20-2	1	0.50	0.134	0.268	0.63	0.150	0.237
WBE-20-3	2	0.50	0.039	0.077	----	-----	-----
WBE-30-1	3	6.78	1.008	0.149	7.41	0.106	0.143
WBE-30-2	3	1.28	0.412	0.322	1.53	0.448	0.293
WBE-30-3	3	0.42	0.099	0.235	0.58	0.109	0.189
SIL-10-1	1	0.54	0.152	0.281	0.68	0.169	0.249
SIL-10-2	1	0.59	0.078	0.133	0.74	0.087	0.118
SIL-10-3	1	0.50	0.074	0.149	0.63	0.083	0.131
SIL-20-1	1	0.48	0.045	0.094	0.61	0.050	0.082
SIL-20-2	1	0.44	0.032	0.072	0.57	0.035	0.062
SIL-20-3	2	0.47	0.059	0.126	----	-----	-----
SIL-30-1	3	0.49	0.075	0.152	0.66	0.082	0.125
SIL-30-2	3	0.45	0.067	0.150	0.63	0.075	0.118
SIL-30-3	3	0.36	0.063	0.175	0.52	0.070	0.134

Note: Averages are an average of 9 measurements.

these transformations was performed and the comparison for the control, water-based epoxy, and silane treatments is shown in Table 4.8. It is observed that for identical treatments, times, and depths, the standard deviation typically increased, the chloride content increased, and the coefficient of variation slightly increased when the added linear regression was included.

4.2.4. Chloride Ion Profiles

The chloride ion profiles were plotted with the results from the average of the measurements from the same treatment, week, and depth. Only the first three depths of each sampling location were analyzed since the third depth of all treatments and weeks represented background chloride levels. Chloride analysis data are detailed in Appendix B.

4.2.4.1. Horizontal Specimens

The results of the chloride ion profiles for the horizontal specimens are tabulated in Table 4.9. A graph for each treatment is seen in Figures 4.15-4.19. A summary of the increases in chloride content (background subtracted) and the ratio of these increases of treatments over control are displayed in Table 4.10. Only the ratios for depth 1 of weeks 10 and 20 and for depths 1 and 2 of week 30 are calculated. This was because the increase in chlorides at other depths and times were below 0.20 lb/yd^3 which would yield questionable results when using these values in a

**Table 4.9 Summary of Average Chloride Contents for Horizontal Specimens
(all values in lb/yd³)**

	Depth	CTL	WBE	SBE	SIL	SLX
Week 10	1	2.33	1.62	2.12	0.54	0.50
	2	0.68	0.66	0.69	0.59	0.53
	3	0.49	0.50	0.50	0.50	0.52
Week 20	1	4.10	3.19	3.95	0.48	0.50
	2	0.61	0.50	0.67	0.44	0.47
	3	0.48	0.50	0.50	0.47	0.47
Week 30	1	7.32	6.78	7.26	0.49	0.44
	2	1.46	1.28	1.36	0.45	0.47
	3	0.37	0.42	0.41	0.36	0.39

(Note: 1 lb/yd³ = 0.595 kg/m³)

Averages are an average of 9 measurements.

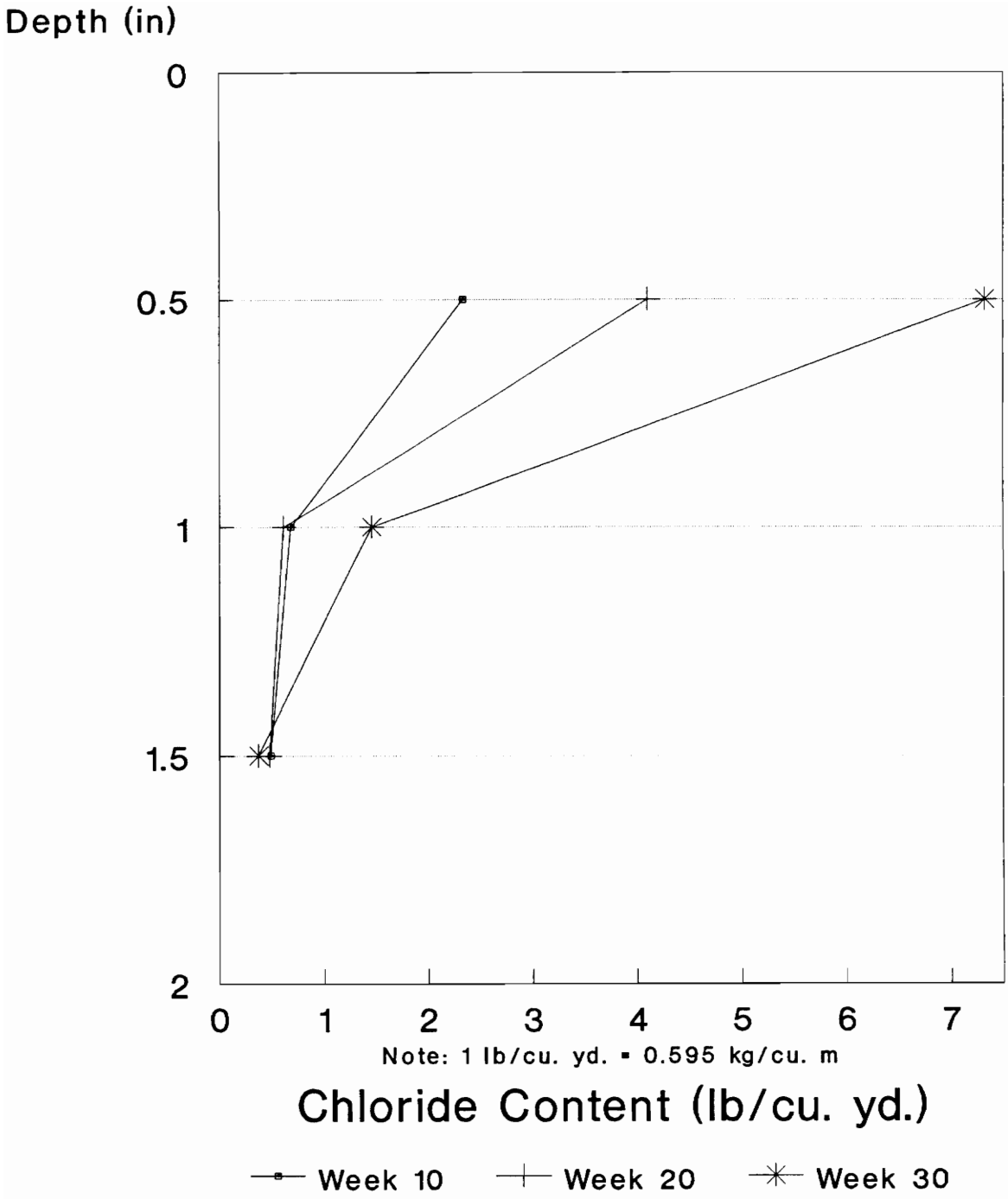
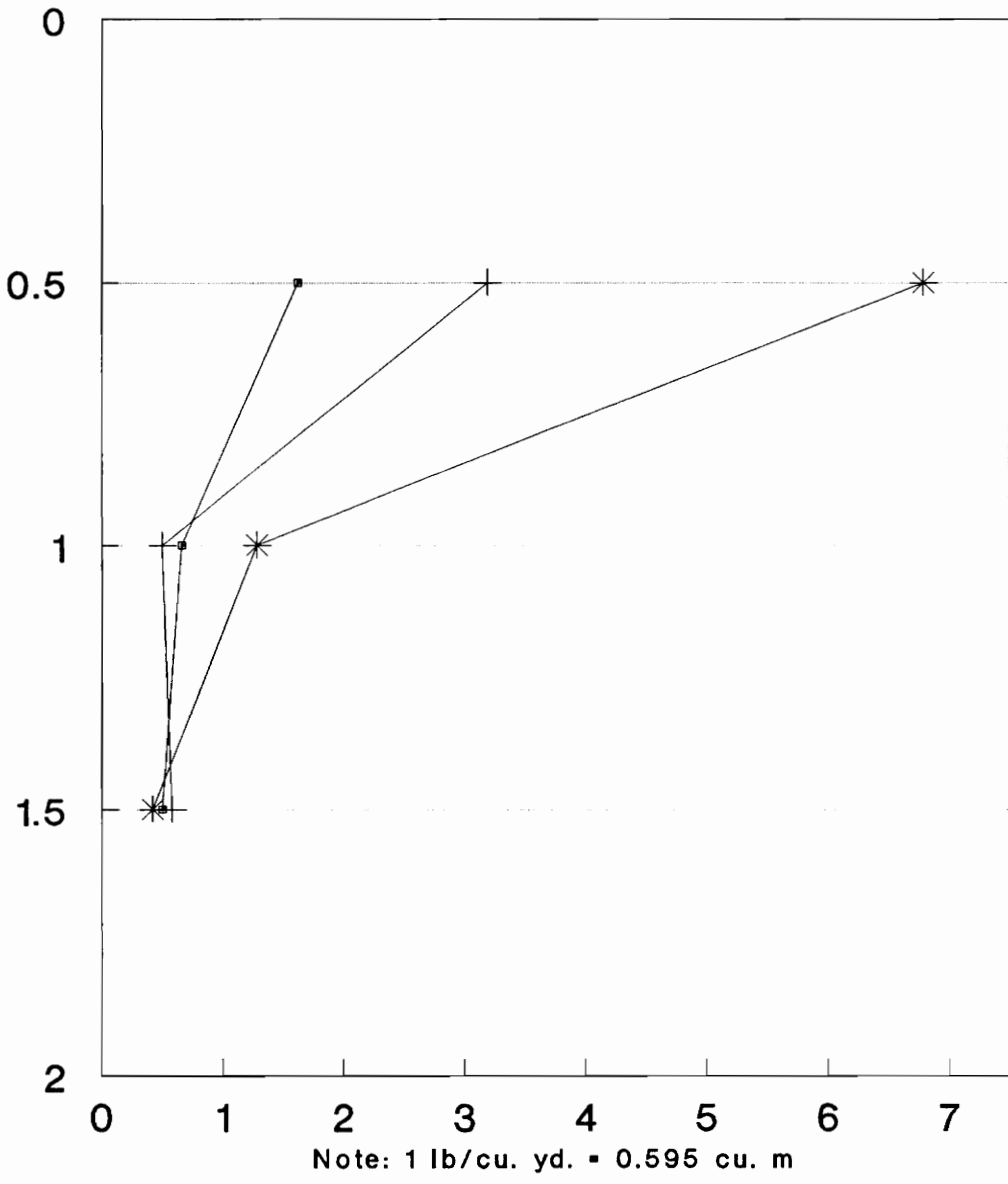


Figure 4.15 Average Chloride Content Profile: Control Slabs

Depth (in)

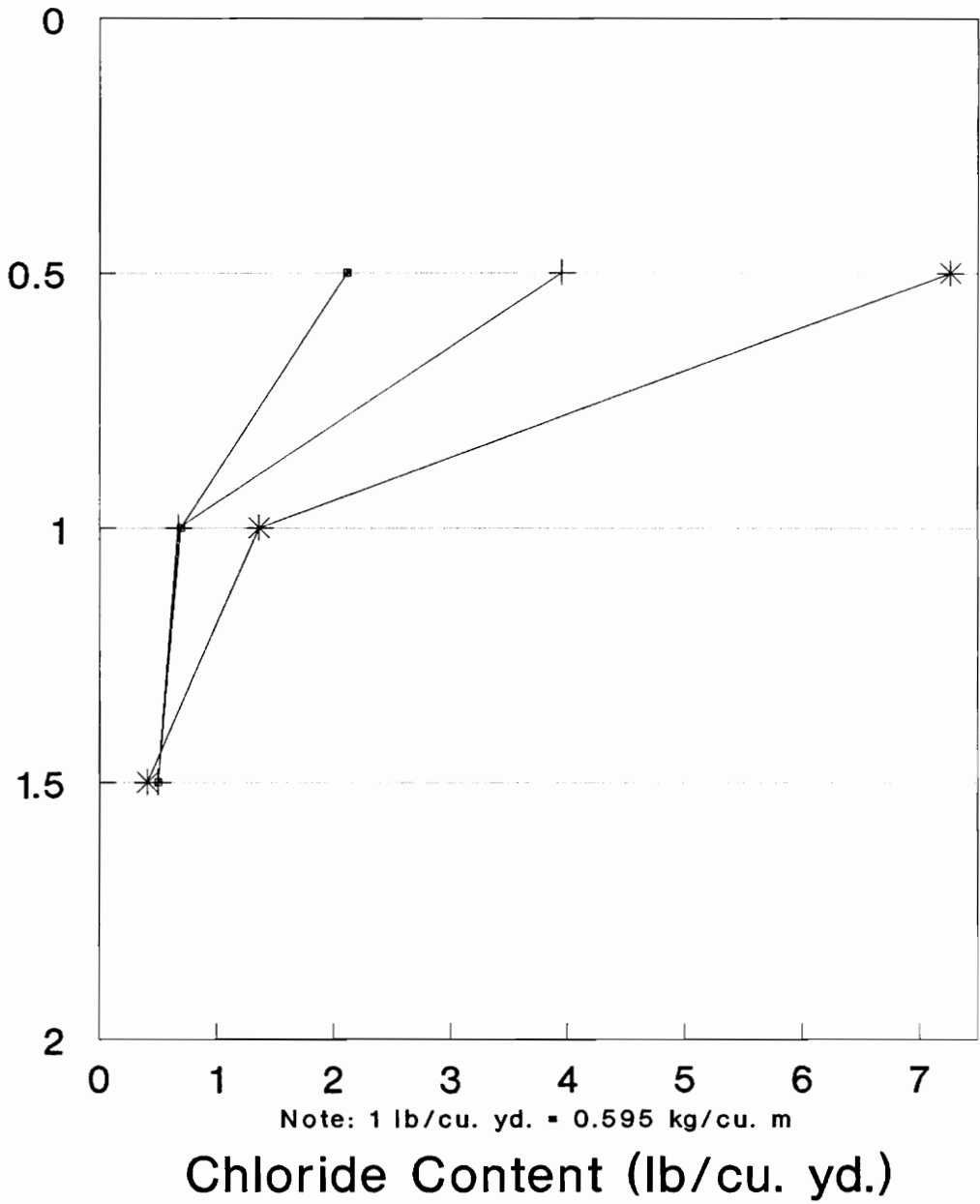


Chloride Content (lb/cu. yd.)

—•— Week 10 —+— Week 20 —*— Week 30

Figure 4.16 Average Chloride Content Profile: Water-Based Epoxy on Slabs

Depth (in)

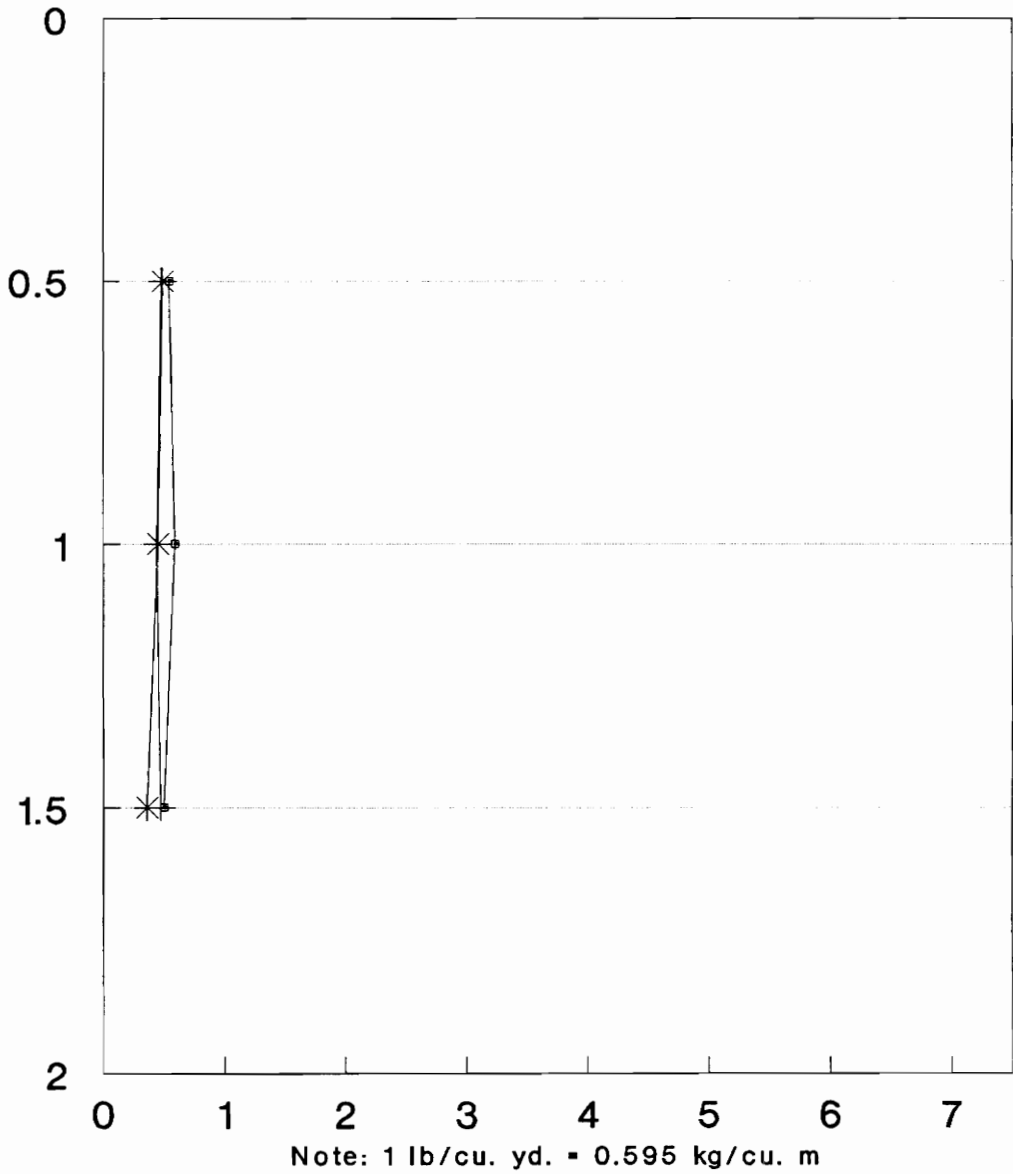


Chloride Content (lb/cu. yd.)

—•— Week 10 —+— Week 20 —*— Week 30

**Figure 4.17 Average Chloride Content Profile:
Solvent-Based Epoxy on Slabs**

Depth (in)



Chloride Content (lb/cu. yd.)

—■— Week 10 —+— Week 20 —*— Week 30

Figure 4.18 Average Chloride Content Profile:
Silane on Slabs

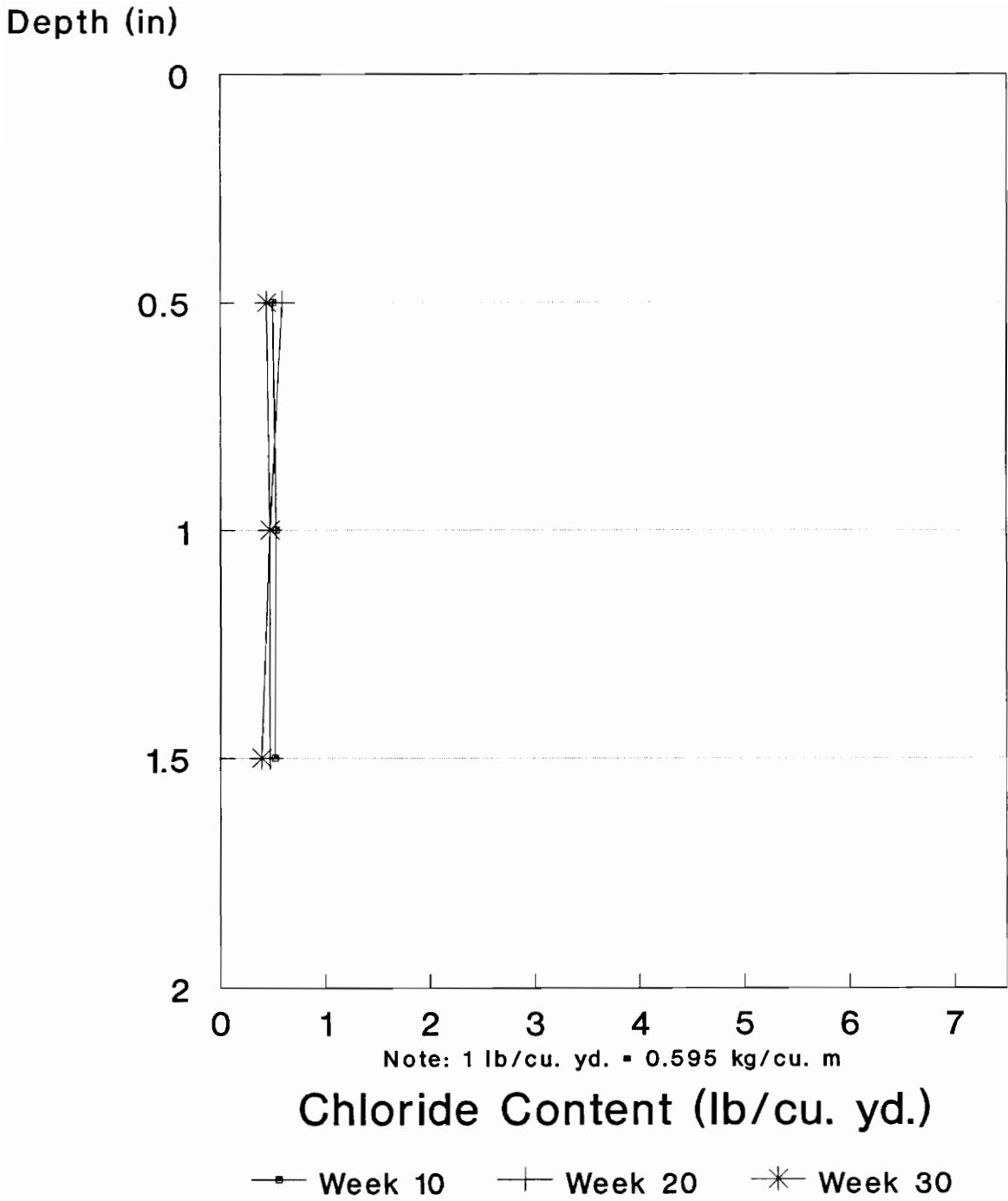


Figure 4.19 Average Chloride Content Profile:
Siloxane on Slabs

Table 4.10 Summary of Average Chloride Content Increases and Treatment/Control Data for Horizontal Specimens (all chloride values in lb/yd³)

Depth		CTL		WBE		SBE		SIL		SLX	
		Cl over bkgd	Trtmt CTL	Cl over bkgd	Trtmt CTL	Cl over bkgd	Trtmt CTL	Cl over bkgd	Trtmt CTL	Cl over bkgd	Trtmt CTL
Wk	1	1.83	1.00	1.12	0.61	1.62	0.89	0.04	0.02	0.00	0.00
10	2	0.18	1.00	0.16	----	0.19	----	0.09	----	0.03	----
	3	-0.10	1.00	0.00	----	0.00	----	0.00	----	0.02	----
Wk	1	3.62	1.00	2.71	0.75	3.47	0.96	0.00	0.00	0.02	0.01
20	2	0.12	1.00	0.02	----	0.19	----	-0.04	----	-0.01	----
	3	0.00	1.00	0.02	----	0.02	----	-0.01	----	-0.01	----
Wk	1	6.93	1.00	6.39	0.92	6.87	0.99	0.10	0.01	0.05	0.01
30	2	1.07	1.00	0.89	0.83	0.97	0.91	0.06	0.06	0.08	0.07
	3	-0.02	1.00	0.03	----	0.02	----	-0.03	----	0.00	----

(Note: 1 lb/yd³ = 0.595 kg/m³)

denominator.

It is noted that the amount of chlorides at the first depth increased to a greater extent between cycles 20 and 30 than between the first two 10-week cycles. This may be due to the higher temperatures experienced during the ponding periods in the summer days of final third of the pondings. Since the ratio of the sealed to control sections remains about the same, it appears that whatever the cause was, it affected all treatments the same. A slight increase in the ratios is noted for the ratios of the epoxies over time. This is seen as the evidence of the breakdown of the sealers. The silane and siloxane treatments, remaining well below 10% ratios, did not appear to deteriorate appreciably over time.

4.2.4.2. Vertical Specimens

The results of the chloride ion profiles for the vertical specimens are tabulated in Table 4.11. A graph for each treatment is shown in Figures 4.20-4.24. The chloride increases and ratios are displayed in Table 4.12. The most notable difference between the vertical specimen chloride data and that of the horizontal specimens is the variation in the epoxies. While still not nearly as impressive in performance as the penetrating sealers, the epoxies on the wall prevented proportionally less chlorides from entering into the concrete in comparison to the control section of the wall than the epoxies on the slabs when compared to the control slabs. The difference in chloride exposure times did not account for this since the

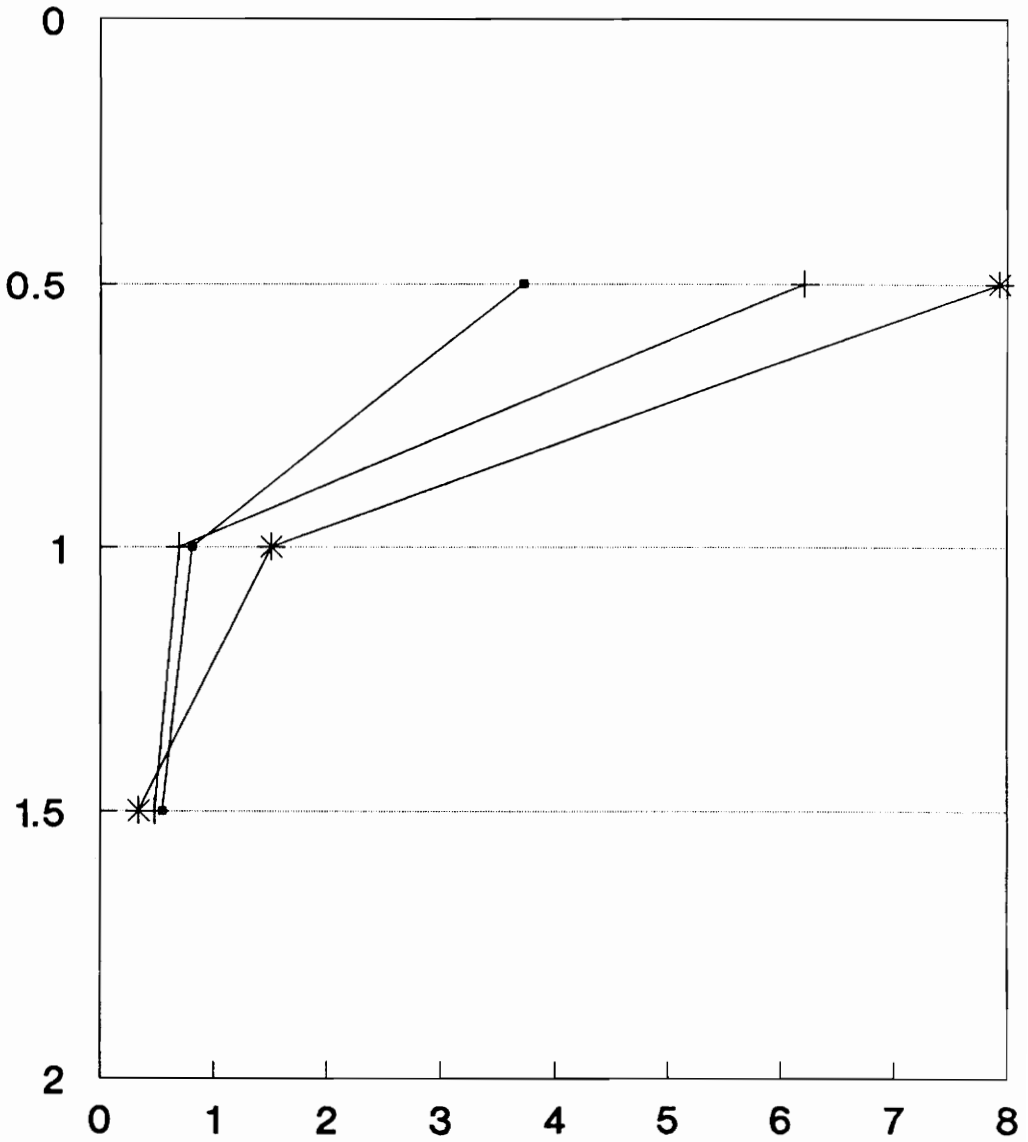
**Table 4.11 Summary of Average Chloride Contents for Vertical Specimens
(all values in lb/yd³)**

	Depth	CTL	WBE	SBE	SIL	SLX
Week 11	1	3.73	0.87	0.92	0.59	0.52
	2	0.81	0.60	0.53	0.51	0.57
	3	0.55	0.55	0.52	0.49	0.50
Week 21	1	6.21	1.19	1.57	0.69	0.72
	2	0.70	0.51	0.61	0.50	0.47
	3	0.48	0.48	0.47	0.48	0.51
Week 30	1	7.93	2.13	2.97	0.57	0.89
	2	1.51	0.35	0.59	0.31	0.31
	3	0.34	0.27	0.30	0.26	0.32

(Note: 1 lb/yd³ = 0.595 kg/m³)

Average values are an average of 5 measurements.

Depth (in)



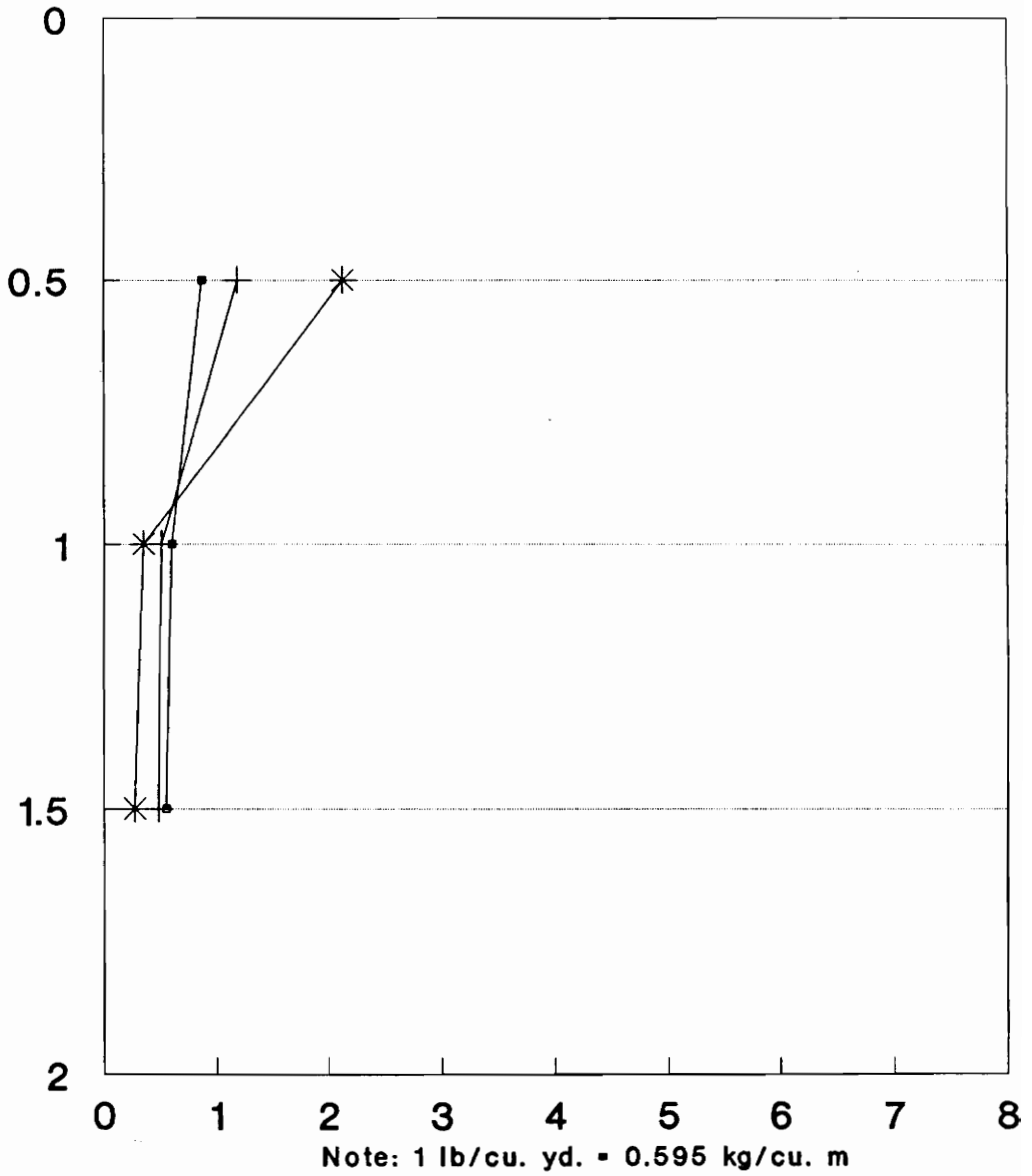
Note: 1 lb/cu. yd. = 0.595 kg/cu. m

Chloride Content (lb/cu. yd.)

—●— Week 10 —+— Week 20 —*— Week 30

**Figure 4.20 Average Chloride Content Profile:
Control Wall Section**

Depth (in)

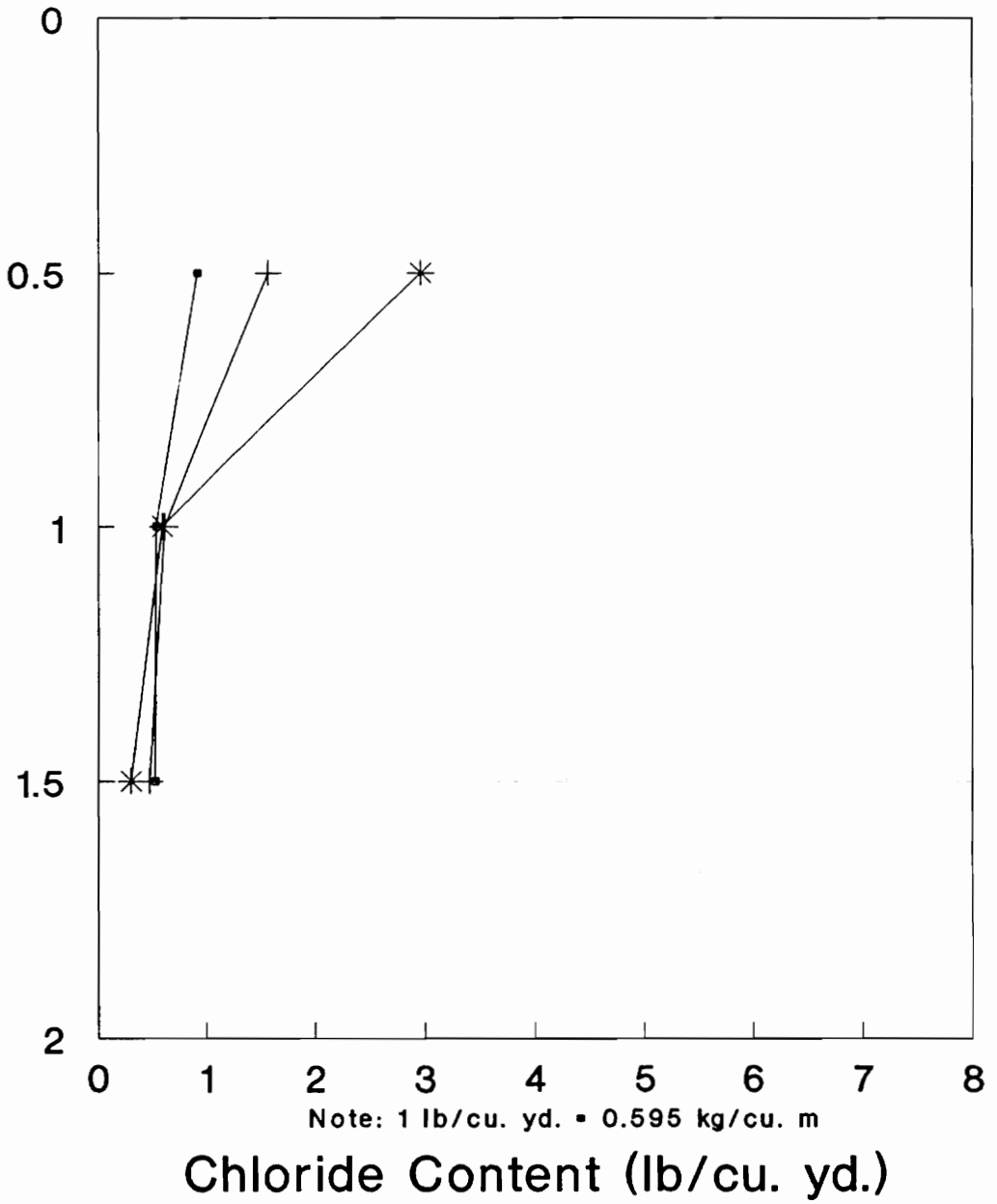


Chloride Content (lb/cu. yd.)

—●— Week 10 —+— Week 20 —*— Week 30

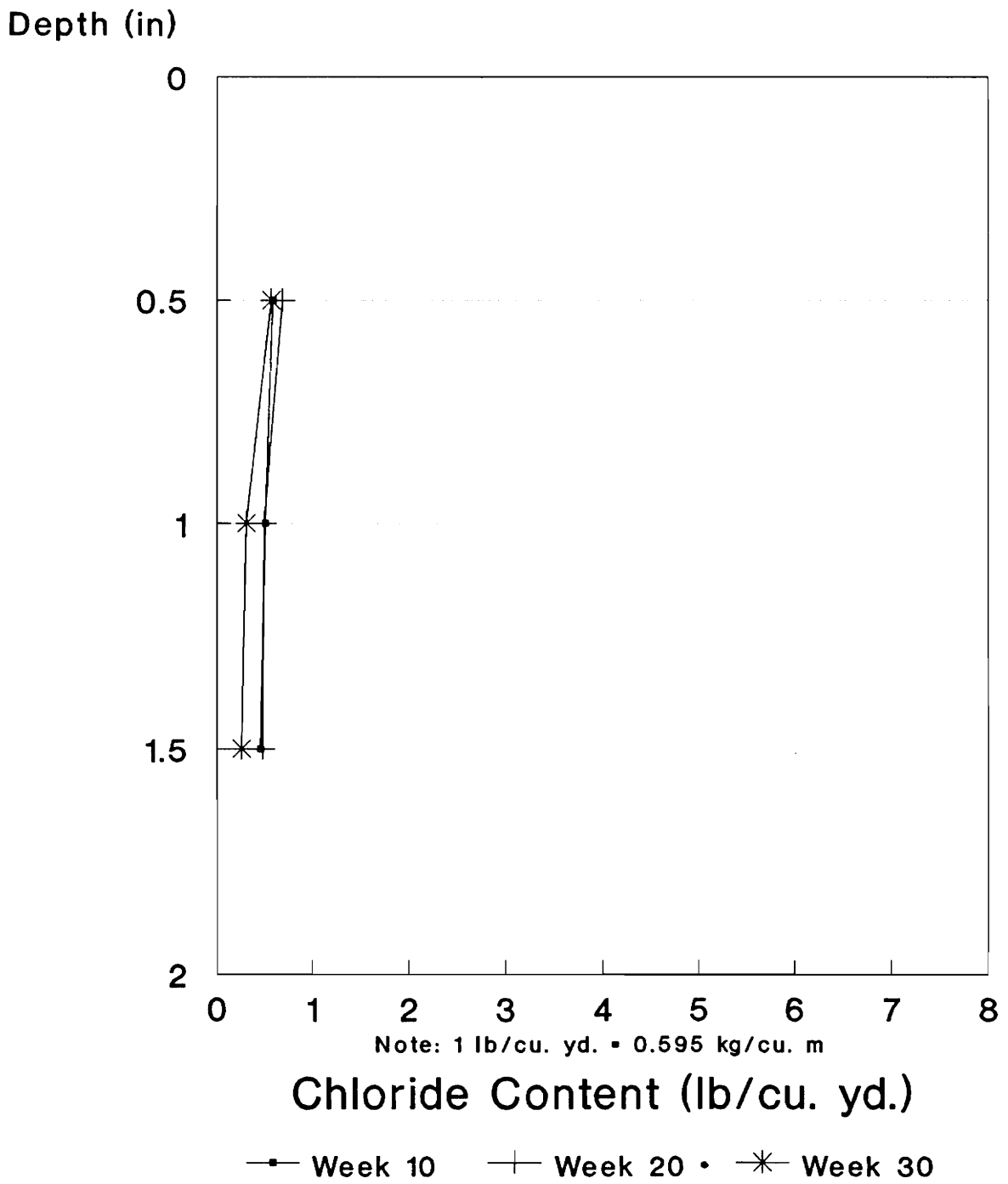
Figure 4.21 Average Chloride Content Profile:
Water-Based Epoxy on Wall

Depth (in)



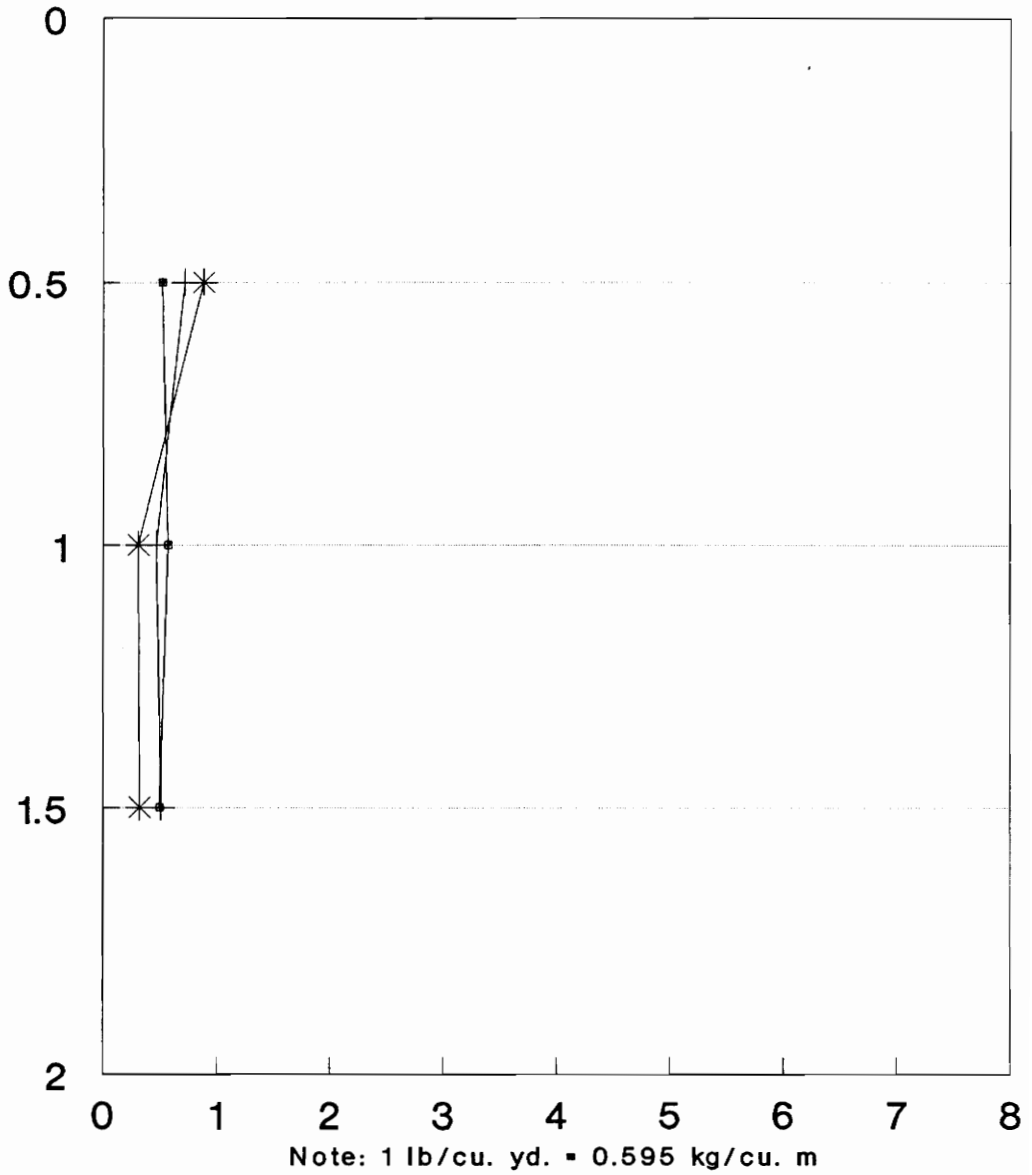
—●— Week 10 —+— Week 20 —*— Week 30

Figure 4.22 Average Chloride Content Profile:
Solvent-Based Epoxy on Wall



**Figure 4.23 Average Chloride Content Profile:
Silane on Wall**

Depth (in)



Chloride Content (lb/cu. yd.)

—■— Week 10 —+— Week 20 —*— Week 30

Figure 4.24 Average Chloride Content Profile:
Siloxane on Wall

Table 4.12 Summary of Average Chloride Content Increases and Treatment/Control Data for Vertical Specimens (all chloride values in lb/yd³)

Depth		CTL		WBE		SBE		SIL		SLX	
		Cl over bkgd	<u>Trtmt</u> CTL	Cl over bkgd	<u>Trtmt</u> CTL	Cl over bkgd	<u>Trtmt</u> CTL	Cl over bkgd	<u>Trtmt</u> CTL	Cl over bkgd	<u>Trtmt</u> CTL
Wk	1	3.23	1.00	0.37	0.11	0.42	0.13	0.09	0.03	0.02	0.01
11	2	0.31	1.00	0.10	----	0.03	----	0.01	----	0.07	----
	3	0.05	1.00	0.05	----	0.02	----	-0.01	----	0.00	----
Wk	1	5.73	1.00	0.71	0.12	1.09	0.19	0.21	0.04	0.24	0.04
21	2	0.22	1.00	0.03	----	0.13	----	0.02	----	-0.01	----
	3	0.00	1.00	0.00	----	-0.01	----	0.00	----	0.03	----
Wk	1	7.54	1.00	1.83	0.24	2.67	0.35	0.27	0.04	0.59	0.08
30	2	1.12	1.00	0.05	0.04	0.29	0.26	0.01	0.01	0.01	0.01
	3	0.04	1.00	-0.03	----	0.00	----	-0.04	----	0.02	----

(Note: 1 lb/yd³ = 0.595 kg/m³)

difference is between ratios of the treatment and control for the same surface. This argument should hold for any major difference strictly between the surfaces. But there were two differences which may have affected the epoxies on the slab surface and not the epoxies on the wall surface. First, the salt water did heat to a greater extent since it was directly in the sun and under the plexiglass covers. The white plastic sheets added on the 19th ponding cycle should have prevented this from being a major factor. But a big difference between the epoxy performances in the first 20 weeks during cold weather demonstrates that this was not a great contributing factor. The second difference was that of exposure to sunlight's ultraviolet radiation. The slab surfaces received almost all of the direct sunlight available for the test period as opposed to the wall which received little light exposure since it was oriented away from the sun. Also, the sunlight which fell on the wall was at a very oblique angle. The interpretation of this data is discussed in the service life section.

The chloride results for the wall also differ from the results for the slab since there is a more even increase in the depth 1 chlorides over all three 10-week cycles along with a smaller increase during the last third of the test. This may be due to the wall being oriented away from the sun, facing approximately N40°W. No heating (above air temperature) of the water was observed in the third segment of the surface wetting times, and the more even increase of chloride ingress would then be expected. Also, the slight levelling off of the week 20 to week 30 chlorides may be a natural reduction as the chloride content approaches its constant concentration under these

conditions.

Although the penetrating sealers stayed at 8% ratios or below throughout, the epoxies on the wall appeared to deteriorate as they did on the slabs. This decay is evident particularly in the last third of the test when chloride content ratios increased to 24% and 35% from levels mostly well below 20%.

It should also be noted that the vertical chloride data was much less consistent than the horizontal chloride data. Many outliers were discarded which may well be due to the higher surface void content (bug holes) and lower surface uniformity evident on the wall.

4.3 Determination of Service Life

4.3.1. Basic Approach for Sealer Life Determination

For most tests which measure the effectiveness of sealers on concrete, a standard for performance or estimation of how long they perform to an acceptable standard is not proposed. A few of the tests do mention vague limits on the laboratory measurements, with standards only proposed in a couple references, as mentioned earlier [8, 14]. Some of the difficulties with the standards of performance proposed thus far are: they bear no direct relationship to chloride diffusion in the field; they do not account for different severities of climate (chloride exposure,

ultraviolet light, traffic wear) or concrete qualities; and they do not consider sealer-concrete interactions which may influence sealer decay.

The method proposed here addresses these issues. The goal of sealer application must be remembered. The initiation of the corrosion of the reinforcement which is trying to be prevented is the point on Figure 2.1 shown as the end of the diffusion period. Sealers should prevent the chloride concentration at the rebar level from reaching corrosion-initiating levels in a 50-year life span of the bridge. The amount of chlorides allowed to "leak" past the surface sealer, and build up at the 0.5" depth is taken here as the driving chloride concentration, C_o . A corrosion threshold value of 1.2 lb/yd³ (0.71 kg/m³) of chlorides in concrete will be used [4]. Therefore, the sealer service life is influenced by the chloride leakage factor, the depth of the rebar, the C_o value which untreated concrete would attain at that location, and the diffusion constant (D_c) of the concrete.

It is recognized that all of the rebar is not at the same depth. For normally distributed reinforcing steel, the standard deviation and mean of the steel depth needs to be known. With this information, a standard needs set for the percent of steel which will be at a depth less than the corrosion threshold depth, a concrete chloride content of 1.2 lb/yd³ (0.71 kg/m³), at a particular time, here using a 50-year bridge life. It has been suggested that this limit should be 2.5% [40]. Whatever the standard, using the information which needs to be obtained for any deck or pier, the mean depth and standard deviation, the calculation of the depth X is accomplished.

For the purposes of this research, the depth X will be taken as 1.61 in., the results from a mean depth of 2.0 in., standard deviation of 0.2 ($2.0 - 1.96(0.20)$), and a specified steel corrosion limit of 2.5%. Again, measurable changes in the depth or standard deviation of the reinforcement in a bridge member would warrant a new calculation of the X value.

The driving concentration, C_o , is more difficult to measure. C_o varies with salt exposure amounts and times. For the purposes here, four values will be used which are the highest levels of different exposure conditions. The categories of exposure, along with the highest concentration (lb/yd^3) for each category from recently measured data, are: Low (4.0), Moderate (8.0), High (10.0), and Severe (15.0) [40]. These means will be used in the C_o - D_c matrix to follow.

The diffusion constant, D_c , is greatly influenced by the quality of the concrete (permeability) and climatic exposure conditions. As with C_o , a range for D_c values will be used which are commonly found in various states. The values used in the matrix are 0.05, 0.09, and 0.13 in^2/yr [40].

Before presenting the sealer service life model and the method of calculations, the present practices and limiting conditions need to be considered. After presenting the leakage factor model for sealer service life, the added effects of traffic wear and ultraviolet light exposure is examined, and finally, the leakage factor matrix service life of the sealers tested is produced.

4.3.2. Present Practices and Limitations on Service Life

There are few citations in literature which address the service life of concrete sealers. The absence of such information leaves little help to the engineer in planning a maintenance schedule.

It should be noted that either in-situ testing (nondestructive or destructive) with some logical failure criteria or a reliable service life estimate is needed for maintenance (reapplication) decisions to be made. Although this research attempts to determine a service life, it has also attempted to correlate a nondestructive testing procedure to chloride ingress in order to include it as an in-situ test. It would be wise for future research and maintenance schedules to include both of these approaches in order to correlate and thus confirm when sealers need reapplication.

4.3.2.1. Present Practices

Present practices in determining the length of time that sealers are "effective" usually deal with subjective intuition which may be grounded in some logical reasoning. For example, one quantitative analysis which has been presented is that of taking cores and comparing water absorption between sealed to unsealed cores. It is suggested that when the ratio of unsealed to sealed absorption is less than or equal to 3, it is time to reseal the concrete [21]. No justification for this threshold is given.

4.3.2.2. Limiting Conditions

The upper limit of sealer service life time needs to be explored. Indeed, if a sealer responds in a test such as conducted in this research by allowing very little chlorides in, then one may think that resealing is never needed. But it is known that traffic wear and ultraviolet light accelerates the breakdown of the sealer, and without these effects, time itself will bring about an eventual failure of the bond between sealer and substrate. This is an important point which emphasizes the need for a reliable in-situ testing program.

It is reasonable then to establish upper limits on service lives based on the extent the surface is exposed to the conditions mentioned above. The deck is typically exposed to UV light and, in the wheel paths, traffic wear. The piers and girders are not exposed to wear but may be exposed to UV light depending on their orientation, climate, and latitude. Indeed, Carter states, "Life expectancy is based on rate of surface abrasion, which is generally a function of traffic volumes" [7], exposure conditions, such as ultraviolet light, and the stability of the sealer to substrate bond [21]. Alberta's entire approval process is based on the exposure locations of the sealers applied, more specifically, 1) traffic bearing surfaces, 2) non-traffic bearing surfaces, and 3) surfaces exposed to public for which aesthetics is of major concern. Within these categories, subcategories exist based on the typical moisture level of the concrete [38]. In Alberta the major (high traffic volume) bridge decks are sealed only with penetrating sealers and resealed on a 4-year schedule.

Less traveled surfaces are resealed every 7 years on average [7].

The concept that maximum sealer service life is dependant on traffic wear is sensible when actual wear is considered. For example, the transverse profile of the I-81 bridge which has an AADT of 24,270 was measured. This was done using a fiberglass I-beam laid across the lane. The differential between the beam and the surface was measured every 6 in. (15 cm). The average profile from these measurements is displayed in Figure 4.25. Considering the surface was placed 27 years ago and assuming its profile was horizontal then, the average wear in the wheel path area has been on the order of 0.0066 in/yr (0.0168 cm/yr). Other surface wear data agree with this order of magnitude in wear [39]. Assuming, as discussed in the background section, that penetrating sealers have typical penetration depths of 0.0625-0.125 in. (0.15-0.30 cm), then it is surmised, using the conservative limits, that the maximum service life of a penetrating sealer on a high volume (20,000-30,000 AADT) deck would be 9-10 years. On less traveled surfaces, the maximum service life due to wear effect may be estimated to be longer. But it must be remembered that the penetration depth is the greatest depth of penetration. Therefore, well before the abrasion of the surface reaches the penetration depth, much of the sealer, and therefore its effectiveness, will have been worn away. To present a sensible cushion for this effect, and to provide a conservative yet reasonable limit, a maximum service life of 8 years, based on wear, is estimated for penetrating sealers on bridge decks. A 10-year limit is placed on penetrating sealers used on piers, girders, parapets, etc.

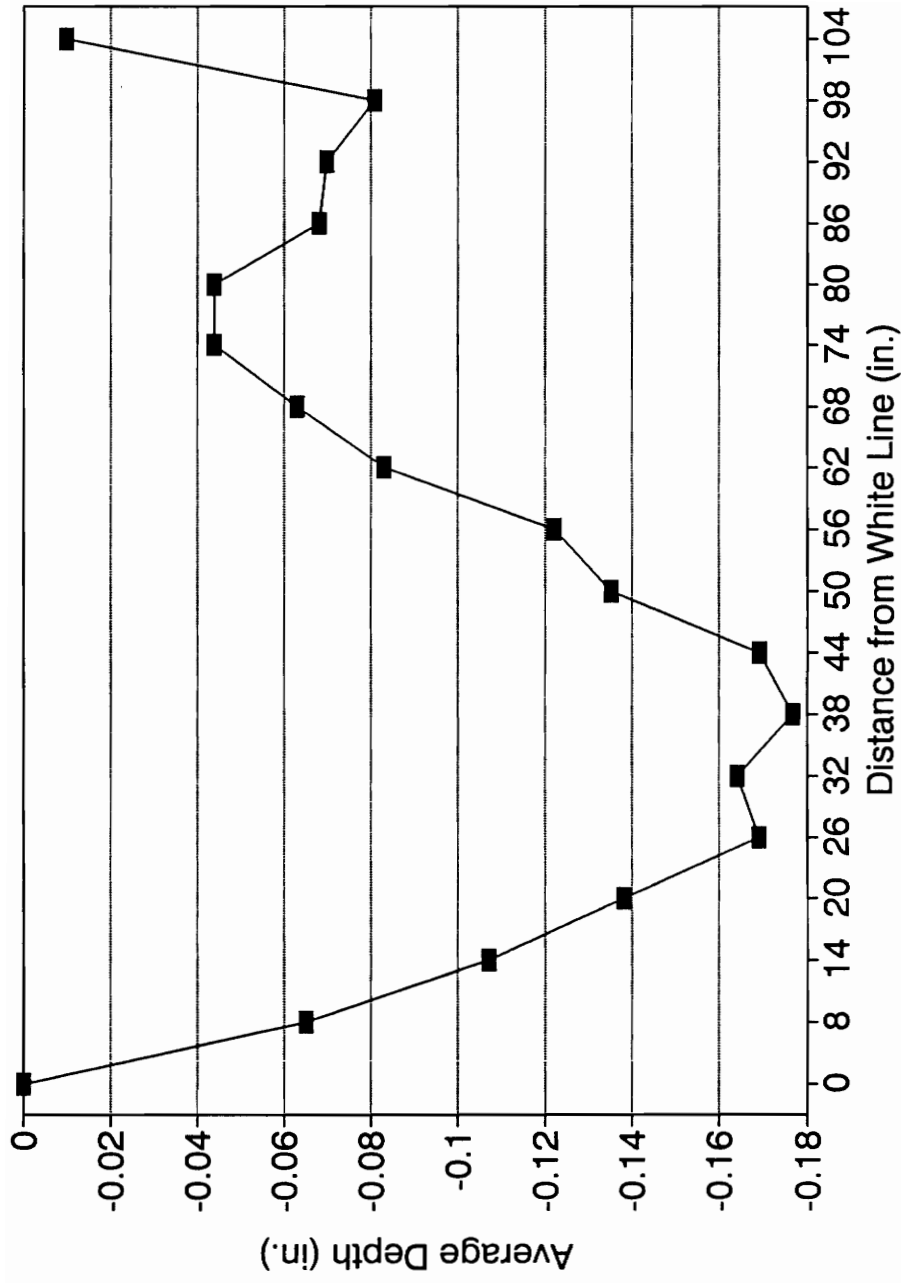


Figure 4.25 Cross-Section of Wheel Path: I-81 Bridge

due to the eventual but unresearched degrading of the sealer over time. The influence of ultraviolet light on the maximum service life should not be significant since it is assumed that the penetrants are hidden from being affected. Evidence to this fact is supported by the good performance of the penetrating sealer in the Series IV southern climate testing phase of NCHRP 244 [15].

For sealers that are nonpenetrants, the maximum service life would depend on the rate of wear of the sealer itself. The thicknesses may vary and resistance to abrasion may be significantly different than the concrete surface it covers. It is thus deduced that, unlike penetrants, the maximum wear-controlling service life of nonpenetrating sealers is far more dependant on the specific chemical formulation of the sealer. Degradation from exposure to ultraviolet light will also affect the maximum service life of these types of sealers. Therefore, climate and latitude must be considered, along with the specific sealer, when determining this maximum service life. The maximum service life for nonpenetrating sealers under any exposure condition is set at 10 years, again due to eventual degrading over time. It should also be noted that visual inspection is all that is often needed in determining whether a coating-type sealer is still present.

4.3.3. Service Life Model

With the above discussion taken into account, the task of determining a service life model is commenced. In similar fashion to the approval lists of Alberta, the

service lives of sealers will be based here on the functional category of the sealer.

These are:

1. Bridge Decks

1a. Lane Region (traffic wear)/UV Exposure

1b. Lane Region (traffic wear)/Minimal UV Exposure

1c. Shoulder Region (minimal traffic wear)/UV Exposure

1d. Shoulder Region (minimal traffic wear)/Minimal UV Exposure

2. Piers and Girders

2a. Ultraviolet Light Exposure

2b. Minimal Ultraviolet Light Exposure

The basic approach in determining the service life of sealers is to determine the service life for the sealers in a "protected" environment and then consider the added effects of traffic and/or ultraviolet light effects. Protected refers to minimal UV and wear exposure, but no protection from temperature or moisture variations. A flow chart of the service life determination is seen in Figure 4.26.

4.3.4. Calculation of Service Life from Testing Program

As discussed, the service life of a sealer is not only dependant on the

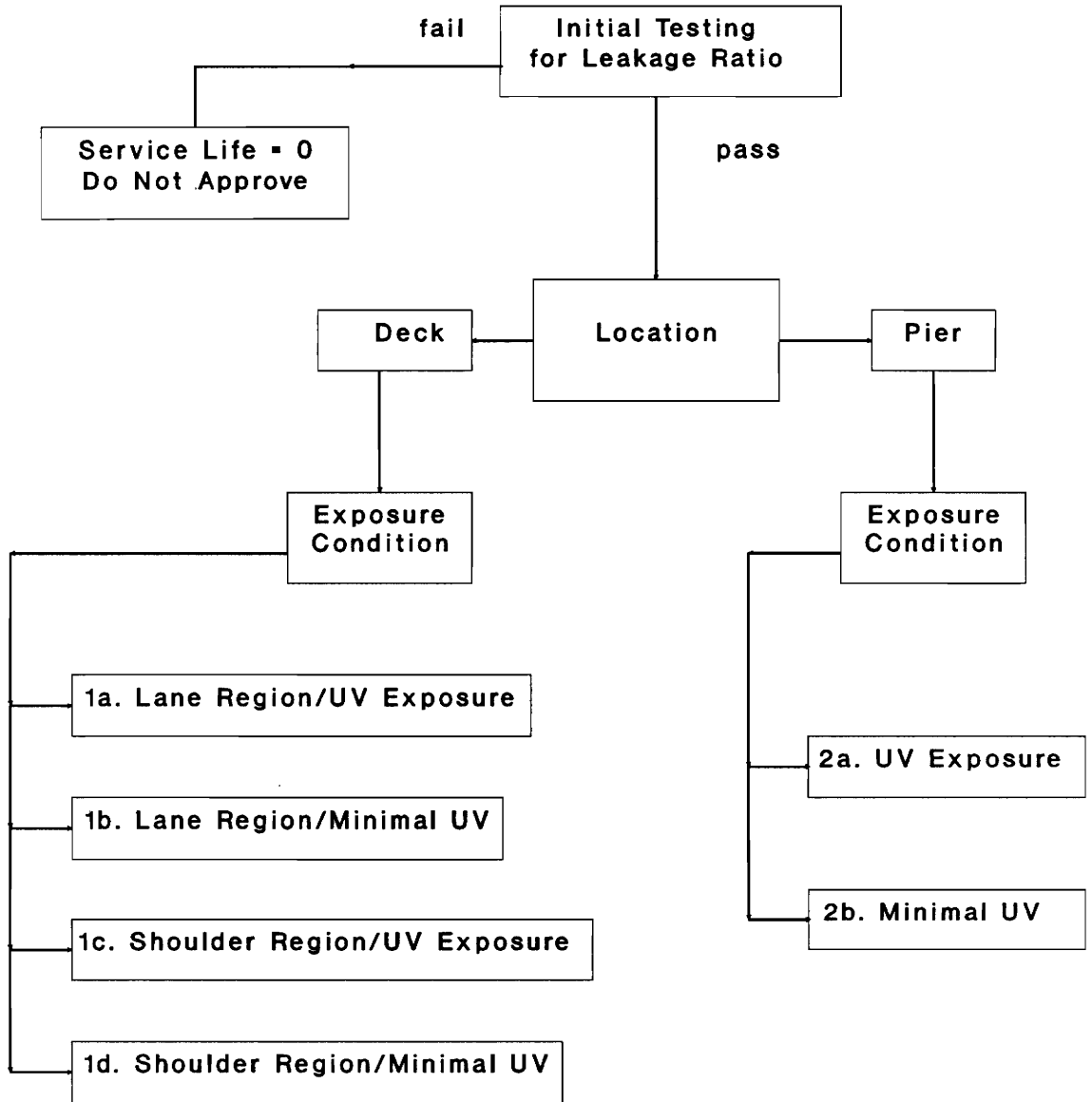


Figure 4.26 Service Life Flow Model

effectiveness of the sealer, but on the site conditions at which the sealer is applied. The five steps in estimating the service life of a sealer based on the amount of chloride leadage are: 1) Estimate the chloride concentration level, C_o , which is allowed to build up over 50 years that will keep the chloride concentration at the selected rebar level below corrosion threshold level, 2) Estimate the equivalent field time which corresponds to 30 weeks of ponding for various combinations of C_o and D_c , 3) For the equivalent time and allowable C_o buildup at various bridge sites' exposure conditions, determine what percent of chlorides is allowed to pass the sealed surface layer, 4) Determine the percent leakage from the laboratory testing and compare this to the allowable leakage percent, and 5) Use a ratio of these percents to estimate the service life of the sealer in question with the specific site conditions.

The level of the chlorides which is allowed to be present at the 1/2" level is first determined. The C_o level under a sealed surface is not constant as is typical for the unsealed surface. Instead, there is a build-up of the chlorides at this level as the sealer only allows a certain amount to leak past the sealed surface. With a constant rate of chloride leakage, the total build up of chlorides, here termed $C_{o-total}$ for any particular D_c was calculated. For the depth of 1.61 in. and a time of 50 years, the results are: for $D_c = 0.05 \text{ in}^2/\text{yr}$, $C_{o-total} = 4.88 \text{ lb/yd}^3$; for $D_c = 0.09 \text{ in}^2/\text{yr}$, $C_{o-total} = 4.06 \text{ lb/yd}^3$; for $D_c = 0.13 \text{ in}^2/\text{yr}$, $C_{o-total} = 3.62 \text{ lb/yd}^3$. These values were estimated using a standard solution to Fick's Second Law, which is:

$$C_{(x,t)} = C_o[1 - \text{erf}(X/2\sqrt{D_c t})]$$

where,

$C_{(x,t)}$ = chloride concentration at depth x after time t

C_o = driving equilibrium chloride concentration, taken as the chloride concentration at the 1/2 in. level, here depth 1

erf = error function

D_c = chloride diffusion constant

t = time, here taken as 50 years

X = depth at which chloride content is calculated, here representing the depth to the rebar, taken as 1.61 in.

The C_o value calculated from this equation is considered the average chloride level.

With a constant rate of chloride leakage, the value for $C_{o\text{-total}}$ is twice this value.

For example, if $D_c = 0.09 \text{ in}_2/\text{yr}$, $C_o = 2.03 \text{ lb}/\text{yd}_3$, making $C_{o\text{-total}} = 4.06 \text{ lb}/\text{yd}_3$.

It should be noted that this solution is an approximation assuming an average C_o for the 50-year time period. A more precise solution could be obtained by solving the differential equation of Fick's Law for a changing C_o .

An estimate of the equivalent field time for particular site conditions is derived by using the 1-in. chloride concentration from laboratory control (unsealed) specimens at the end of 30 weeks of ponding. This value (1.07 lb/yd³ for horizontal specimens, 1.12 lb/yd³ for the vertical sections) is used for $C_{(x,t)}$ in the Fick's Law equation above, with $X = 1.0 \text{ in.}$, the various combinations of C_o and D_c , and solving for field

time exposure equivalency. The resulting time equivalency will be termed t_{eq} . These values are displayed in the C_o - D_c matrixes to follow.

The t_{eq} is used in conjunction with $C_{o-total}$ for the 50 years to determine what the chloride level will be allowed for that time equivalency, here termed C_{o-eq} . This assumes that a constant leakage is permitted. For example, if $t_{eq} = 5$ years and $C_{o-total} = 4.50$ lb/yd³, then using straight line interpolation, $C_{o-eq} = 0.45$ lb/yd³. Using the C_{o-eq} for that exposure condition, assuming it to be present at the surface, the allowable Leakage Ratio ($LR_{allowed}$) for that location is determined for the time-equivalent. This is done by taking the C_{o-eq} and dividing by the C_o present without the sealer in those conditions. Continuing the above example, if $C_{o-eq} = 0.45$ lb/yd³ and the C_o for that environment was 9.0 lb/yd³, then the $LR_{allowed} = 0.05$, or 5%.

The Leakage Ratio (LR) of any particular sealer is determined by dividing the chloride concentration at week 30 - depth 1 (1/2") of the sealed surface by the same value for the unsealed surface. This value was used since, after analyzing the chloride ion profiles of the control slabs and wall sections, it was noted that the difference in the 1/2-in. measurement was about equal at 30 weeks after being significantly different in earlier weeks. This indicates that the C_o value of the lab concrete was reaching its constant value. These Leakage Ratios are the ratios calculated and displayed earlier in Tables 4.10 and 4.12. If this value is less than the $LR_{allowed}$ for the site condition, then the service life is at least the time-equivalent for that site. If the measured LR is below the $LR_{allowed}$, then the service life is shorter

than the time-equivalent value for those conditions.

Assuming a constant decay of the sealers, the service life can be estimated by using a ratio of the LR's and the time-equivalent. For example, if the $time_{eq}$ were 4 years, and the $LR_{allowed}$ was 0.080, a sealer with a measured LR of 0.040 would be estimated to have a service life of 8 years and a sealer with a LR of 0.160 would be estimated to have a service life of 2 years.

4.3.5. Added Effects

When a sealer has satisfactory leakage factor, then the additional effects are added. For Category 1a. sealers, this factor is traffic wear and greater UV light exposure. For Category 1b. sealers, this factor is traffic wear only. For 1c sealers, UV light exposure is factored in, while category 1d would have no added effects and the service life would not be altered from the originally measured value.

4.3.5.1. Surface Wear

For this research, the only way for the effect of surface wear to have been measured would have been for the Surface Absorption Test to have accurately assessed sealer performance in the field test sections. Unfortunately, as discussed earlier, the difficulties with the SAT prevented even general conclusions of the effect of traffic wear on sealers over time. Future research needs to be done in order to attain a good indication of this effect.

Even though precise effects could not be calculated, general comments on surface wear can be made. Since the epoxies were fairly visible due to the discoloration of the surface, visual observations could be made which gave indications of whether the sealer was present in the wheel path. Although it was easily noted by close visual observation, the photographs in Appendix C indicate that the epoxies wore off in the wheel path well within one year after application. Had these sealers passed the test measuring its leakage factor without added effects, their use would have been restricted to minimal wear surfaces, essentially, shoulders and piers.

The question remains whether penetrating sealers are affected to any appreciable amount by traffic wear. Theoretically, since they do penetrate, the only restriction would be the maximum sealer service life on travelled surfaces, as discussed earlier. This conclusion can not be confirmed to be correct until future testing affirms its validity, especially in light of the data obtained from the SAT results from the bridges. Obviously, penetration depth and the nature of penetration influence how much effect traffic wear truly has. For the purposes of this research, the concept that traffic wear has minimal effect on penetrating sealers will be used.

The categories in the model regarding differences in surface wear are differentiated between being in the travelled lane (wear) or being on a shoulder or a pier (no wear).

4.3.5.2. Ultraviolet Light

The effect of ultraviolet light (UV) in accelerating the breakdown of sealers also needs a great deal of research to quantify. However, some information can be gathered from this research. This is due to the fact that the two laboratory specimen surfaces, slabs and wall, experienced a large difference in the amount of UV light exposure, which may account for the differences in performance of the epoxies between the two surfaces.

The slabs were exposed, as most bridge surfaces are, to direct sunlight. Under the laboratory conditions in this research, the slabs were located with small embankments toward the sunrise and sunset direction. This meant that the slabs were exposed to an average of 10 sunlight hours daily throughout the year. Considering an average of approximately 60% [41] of sunlight hours throughout the year, the slabs would experience about 2200 hours of sunlight yearly. It should be noted, however, that during the ponding times the plexiglass cover prevented approximately 60-80% [42] of ultraviolet radiation from reaching the slabs in the first 18 cycles. The thin layer of water cover during the ponding cycles absorbed only a few per cent of the UV radiation from reaching the surface, as surmised from transmittance data of distilled water [42]. From cycles 19 to 30, no UV light reached the surface due to the white plastic sheets. Therefore, for the 30 weeks of ponding, an estimated equivalency of 950 hours of sunlight reached the surface.

Since the wall faced N40°W, it received no direct sunlight for close to 1/2 of

the year. It is estimated that the wall surface received on the order of 325 hours of sunlight per year, or about 190 hours in the 30 weeks of surface wetting. This means the wall experienced only 20% of sunlight exposure when compared to the slabs. However, it must be noted that the sunlight on the wall surface was at an oblique angle, and this caused the intensity ratio of ultraviolet light on the wall versus the slabs to be well under 20%. With this in mind, the wall could easily be said to have minimal UV light exposure, as do most pier faces which face away from the sun.

In response to this data, an estimate of the effect of ultraviolet light exposure can be made. As mentioned earlier, different chloride ratios between the same sealed section on the wall versus the slabs may well be the result of differences in UV light exposure. A summary of these differences is displayed in Table 4.13. To lend support to the idea of the UV light causing deterioration of the epoxy sealers is the observation that the biggest increase in ratios on the vertical surface occurred in between week 20 and week 30, which was during the summer months, the highest light exposure times for the wall surface. With respect to that, the values for week 20, before much UV degradation could occur on the wall surface, will be used in an estimate of the UV effect. It can be seen that the UV light may well destroys the protection ability of the epoxy sealers. Obviously, if dealing with a need for leakage ratios to be well under a few per cent for widespread use, deterioration at the rates seen by these epoxies would make their use highly questionable. However, under the categories with minimal UV exposure, the initial testing without the added effects

Table 4.13 Comparison of Epoxy/Control Chloride Content Ratios Between Vertical (minimal UV) and Horizontal Surfaces (UV exposure) using Week 30 - Depth 1 Data

Depth		Water-Based Epoxy		Solvent-Based Epoxy	
		Slab	Wall	Slab	Wall
Week 10	1	0.61	0.11	0.89	0.13
Week 20	1	0.75	0.12	0.96	0.19
Week 30	1	0.92	0.24	0.99	0.35

would determine the use of the epoxies under these restrictions.

The amount of ultraviolet light which would fall on the slabs if left uncovered for a year could be estimated to be between the UV exposure intensities of the northern and southern regions as described in NCHRP 244 [15] and reported in Table 4.14. The values for Virginia, the site of this research are roughly interpolated estimates from the other data considering that Virginia lies between the latitudes of the northern and southern cities. Due to the limitations caused by the plexiglass and white plastic covers, the actual amount of UV the slabs were exposed to should be much closer, if not below, the value for UV exposure of the northern climate regions. Therefore, when it is considered that a relatively small amount of UV light actually caused the decay seen in the epoxy sealers on the horizontal surfaces throughout the test time and on the vertical surfaces in the last third of the test time, it is prescribed that any appreciable amount of UV exposure should place a surface in the high UV exposure categories. This leads to the conclusion that only piers facing away from the sun or decks shielded from exposure can be considered in minimal UV exposure categories. Of course, this conclusion is drawn from these two epoxies, and it is acknowledged that other sealers prone to UV decay may behave differently. In other words, other sealers may be affected by UV light but not nearly to the extent of these nonpenetrating epoxy sealers tested here.

When the penetrating sealers are considered, the variation of the chloride ratios are minor, with greater measured chlorides from the wall where the UV was

Table 4.14 Typical Ultraviolet Light Exposures for Various Locations [15]
(all values in watt-hours/sq meter/month)

Location	Winter	Summer
Chicago	2460	8470
New York	2380	6520
Virginia	3200	9000
Phoenix	4650	9980
Miami	4600	6700

(Values for Virginia are estimated by interpolation.)

less. This leads to the conclusion that the penetrating sealers are not affected to any appreciable degree by ultraviolet radiation.

4.3.4. Service Life of Sealers Tested

To determine the service lives of the sealers tested, the calculations as described earlier were done. The service life for each sealer was calculated for each of the different environmental and concrete quality conditions as described by the diffusion constant and driving chloride concentration. Any added effects need to be incorporated, as well, which may result in the exclusion of the sealer from use, or, with further quantification of these effects, a reduction in the service life for that particular situation. It should be noted that the testing on the slabs were not truly a protected test as prescribed by the model since UV radiation was seen to be significant for some of the sealers. However, service life statements can be made.

The C_0 - D_c matrixes was generated for the slabs and the wall for the depth $X = 1.61$ in. The time-equivalent for each condition is included in the two matrixes along with the service lives of the silane and siloxane sealers. The matrix for the slabs is displayed in Table 4.15, the matrix for the wall in Table 4.16. Only in the very mild environments with low D_c values is the service life of either epoxy greater than one year and thus recorded. For more severe environments and higher D_c values, the service life of the penetrating sealers were included in order for analysis of the model's results to be easier.

Table 4.15 C_o - D_c Matrix for Sealer Life Determination on Horizontal Specimens
(all values in years)

Environment	C_o used (lb/yd ³)	Diffusion Constant, D_c (in ² /yr)		
		$D_c = 0.05$	$D_c = 0.09$	$D_c = 0.13$
Severe (range: 10-15)	15.0	$t_{eq} = 3.1$ SIL 4.3 SLX 8.7	$t_{eq} = 1.7$ SIL 1.1 SLX 2.1	$t_{eq} = 1.2$ SIL 0.5 SLX 0.9
High (range: 8-10)	10.0	$t_{eq} = 3.8$ SIL 9.8 SLX 10.0	$t_{eq} = 2.1$ SIL 2.6 SLX 5.6	$t_{eq} = 1.5$ SIL 1.1 SLX 2.2
Moderate (range: 4-8)	8.0	$t_{eq} = 4.4$ SIL 10.0 SLX 10.0	$t_{eq} = 2.5$ SIL 4.4 SLX 8.8	$t_{eq} = 1.7$ SIL 1.8 SLX 3.6
Low (range: 0-4)	4.0	$t_{eq} = 8.1$ SIL 10.0 SLX 10.0	$t_{eq} = 4.5$ SIL 10.0 SLX 10.0	$t_{eq} = 3.1$ SIL 10.0 SLX 10.0

Note: If t_{eq} exceeded 10 years, then 10 years was recorded as the maximum service life.

Table 4.16 C_o-D_c Matrix for Sealer Life Determination on Vertical Specimens
(all values in years)

Environment	C _o used (lb/yd ³)	Diffusion Constant, D _c (in ² /yr)		
		D _c = 0.05	D _c = 0.09	D _c = 0.13
Severe (range: 10-15)	15.0	t _{eq} = 3.1 SIL 1.8 SLX 0.8	t _{eq} = 1.8 SIL 0.5 SLX 0.2	t _{eq} = 1.2 SIL 0.2 SLX 0.1
High (range: 8-10)	10.0	t _{eq} = 4.0 SIL 4.4 SLX 2.0	t _{eq} = 2.2 SIL 1.1 SLX 0.5	t _{eq} = 1.5 SIL 0.5 SLX 0.2
Moderate (range: 4-8)	8.0	t _{eq} = 4.6 WBE 1.1 SIL 7.2 SLX 3.3	t _{eq} = 2.6 SIL 1.9 SLX 0.9	t _{eq} = 1.8 SIL 0.8 SLX 0.4
Low (range: 0-4)	4.0	t _{eq} = 8.6 SBE 5.0 WBE 7.3 SIL 10.0 SLX 10.0	t _{eq} = 4.8 SBE 1.3 WBE 1.9 SIL 10.0 SLX 6.0	t _{eq} = 3.3 SIL 5.5 SLX 2.5

Note: If t_{eq} exceeded 10 years, then 10 years was recorded as the maximum service life.

Of the four sealers tested in this research, two were penetrants and two were not. As discussed previously, the epoxies were shown to be extremely sensitive to UV light exposure and can only be suggested for use on surfaces protected from exposure, categories 1b and 2b. Category 1b can not be included due to the visual observations of wear in less than one year on the field test sections. Even then, it is demonstrated that only in mild environments with $D_e = 0.05$ would the service life of either epoxy be greater than 2 years. This makes their use extremely restrictive.

The other two sealers tested were a silane and a siloxane. Both of these performed extremely well on the horizontal tests and nearly as well on vertical surfaces. But as shown in Table 4.15, only in the lower left region of the matrix could these sealers be used for any appreciable time. When analyzing Table 4.16, the slightly poorer performance restricts their use even further. As discussed earlier, since these are both penetrants, surface wear will assumed to be minimal and UV degradation has been shown to be negligible. Although the added effect factors could not be calculated, it is estimated that no decrease in service life would apply to these hydrophobic penetrants.

4.3.7. Further Analysis of Model

A few comments regarding the model and the implications of the results need to be made. First, it is recognized that with the model as it is, very strict requirements are placed on sealer performance. This is understandable considering

the time factor. As a sealer allows chlorides to leak and build up at the 1/2" depth, the amount of time available for diffusion to the bar level causes the LR to be kept very low.

In a related issue, it must be noted that the sensitivity of the model between acceptable performance and unacceptable performance may cause an error in measuring chlorides to affect the results greatly. This needs to be studied further, but more samples and using the standard ASTM chloride analysis method may need to be employed.

The drastic differences between the results between lower and higher diffusion constant environments indicates the absolute necessity of using dense, good quality concrete. Sealer use can not compensate for poor concrete. Also, sealer use in extreme environments needs much more care and attention due to the higher C_o levels encountered.

Finally, it is necessary for decay of the sealers over time to be quantified for various conditions. The results of more specific tests may reduce the maximum service life obtained through the model for any sealer in any category.

5.0.

CONCLUSIONS

Based on the experiments conducted for this research, the following conclusions can be made:

1. An accelerated test of sealers to determine their functional service lives is possible if legitimate correlations between the test parameters and parameters in the field are resolved. These parameters must include the major factors which affect sealer performance, namely: exposure to traffic wear ultraviolet light, and chloride leakage ratios.
2. Although broad generalizations can not be made with regards to generic types of sealers, it has been shown here that the penetrating hydrophobic sealers (silane and siloxane) performed far better than specific epoxies.
3. The silane and siloxane tested in this research performed at such a level as to approve for use in many conditions and to place their service lives at the levels calculated for each category. It was also shown that increased ultraviolet light exposure did not advance the decay of the effectiveness of these sealers.
4. The two epoxy sealers were found to be of extremely limited use, not being approved for any but the mildest conditions. It was also noted that ultraviolet

light exposure may have a great influence on accelerating the deterioration of these sealers.

5. Service life limits may be reasonably placed on all sealers used in the field depending on the exposure conditions.
6. The Surface Absorption Test as used in this research was not helpful in determining the condition of the sealers. This was due to a wide range of variables which affect the outcome of the test, and which can not be easily held constant. SAT measurements may yield very general categories of performance level of sealers if the variables affecting the test are controlled and/or accounted for.

6.0.

RECOMMENDATIONS: FURTHER RESEARCH

Through the experiences encountered while performing this research, a number of questions arose which require more research in order to adequately answer and advance the understanding of concrete sealers. The recommendations for further research are:

1. The "accelerated test" used in this research needs refined in order to include an adequate evaluation of the influences of the added effects of exposure conditions. These could not be detailed in this report due, in most part, to the failure of the SAT to perform satisfactorily. An alternate method could include the analysis of added effects from taking cores in the field over the time period of the test and compare absorption in a laboratory setting between sealed and unsealed surfaces.
2. Further analysis of the relationship between laboratory ponding and surface wetting to field applications of salt needs to be conducted. This could verify the relationship between ponding and time-equivalency in the field.
3. After a method of evaluation is refined, sealers need to be tested under varying application rates, application conditions, and on various types of concrete in order to determine the ideal circumstances for each sealer.

4. After the method is refined, a large number of sealers in all generic categories should be tested in order to develop a sealer service life list for transportation departments to use.
5. From the large number of sealed bridges in use today, comprehensive analysis should be conducted in order to correlate field results under varying conditions to laboratory results.
6. Cost analysis for each sealer needs to be done which would include the service life. This evaluation needs to cover the span of the bridge service life in order for comparisons to be made between sealing and other maintenance activities.
7. Since some sealers have proven to be effective in protecting concrete from chloride intrusion, an investigation into the use of sealers as a part of a comprehensive bridge protection system needs to be conducted. This study should include the idea of "durability redundancy." This term refers to the idea that, just as bridges are not allowed to be built without structural redundancy, bridges should not be protected without multiple "protection paths," each providing the bridge with salt-induced corrosion safety. This would cost more in the short term, but since we cannot rely on any one scheme, and since deterioration is costly, this will ultimately save money.

Finally, it should be stressed that what is needed in the study and use of concrete sealers is a universal test method which fairly evaluates the sealers. Without a consensus, it will be increasingly difficult to compare future work.

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Appendix A

Surface Absorption Data

Table A1 Surface Absorption Test Data for Slabs - Day 49

Treatment	Sample	Location	Day	Temperature	Column Height Reading (cm)													10min-1min	Treatment Average
					00:00	01:00	02:00	03:00	04:00	05:00	06:00	07:00	08:00	09:00	10:00				
Control	S01	1	49	65	16.7	22.1	24	25.5	26.8	27.7	28.6	29.4	30.1	30.7	31.4	9.3	7.77		
	S02	1	49	65	13.9	17.7	19.1	20.3	21.2	22	22.8	23.5	24.1	24.7	25.1	7.4			
	S03	1	49	70	14.4	18.4	19.5	20.5	21.3	22	22.9	23.6	24.2	24.6	25	6.6			
Water-Based Epoxy	S04	1	49	70	17.7	20.3	21.2	21.7	22.2	22.4	22.7	22.9	23.2	23.4	23.8	3.5	2.57		
	S05	1	49	70	13.9	15.5	15.7	15.8	15.9	16.1	16.2	16.3	16.9	17.2	17.3	1.8			
	S06	1	49	70	17	19.1	19.6	20	20.1	20.2	20.5	20.9	21.2	21.3	21.5	2.4			
Solvent-Based Epoxy	S07	1	49	70	16.9	18.7	19.2	19.4	19.5	19.7	19.8	19.9	20.1	20.1	20.2	1.5	1.53		
	S08	1	49	70	14.5	19.7	20.5	20.8	21	21.2	21.3	21.4	21.5	21.7	21.8	2.1			
	S09	1	49	65	15.8	17.7	18.1	18.2	18.3	18.4	18.4	18.5	18.6	18.7	18.7	1			
Silane	S10	5	49	56	14.3	19.2	19.8	20.2	20.4	20.6	20.9	21	21.2	21.3	21.4	2.2	1.8		
	S10	1	49	65	17	20.3	20.6	20.8	21	21.1	21.2	21.3	21.4	21.5	21.6	1.3			
	S11	5	49	60	15	17.9	18.2	18.5	18.8	19	19.2	19.4	19.5	19.7	20.1	2.2			
	S11	1	49	65	14.4	16.7	17.1	17.3	17.4	17.5	17.6	17.7	17.8	17.9	18	1.3			
	S12	5	49	60	16.5	19.3	19.8	20.1	20.3	20.5	20.7	20.9	21.1	21.2	21.3	2			
Siloxane	S13	1	49	65	17.2	19.4	19.6	19.8	19.9	19.9	20	20.1	20.1	20.2	20.3	0.9	1.48		
	S13	5	49	60	13.1	16.6	17	17.4	17.6	17.7	17.9	18	18.2	18.3	18.5	1.9			
	S14	1	49	61	15.6	18	18.4	18.7	18.9	19.1	19.2	19.4	19.5	19.6	19.7	1.7			
	S14	5	49	60	14.7	16.8	17.1	17.4	17.5	17.6	17.8	18	18.1	18.2	18.3	1.5			
	S15	5	49	61	16	19.1	19.3	19.5	19.7	19.9	20	20.1	20.3	20.4	20.5	1.4			

Table A2 Surface Absorption Test Data for Slabs - Day 50

Treatment	Sample	Location	Day	Temperature	Column Height Reading (cm)														10min-1min	Treatment Average
					00:00	01:00	02:00	03:00	04:00	05:00	06:00	07:00	08:00	09:00	10:00					
Control	S01	9	50	70	16.8	22	23.5	24.4	25.3	26	26.6	27.1	27.6	28.1	28.5	6.5	7.33			
	S02	3	50	60	15.9	24	25.7	26.9	27.9	28.7	29.5	30.1	30.7	31.3	31.7					
	S03	9	50	70	16.9	21.1	22.6	23.6	24.5	25.3	26	26.6	27	27.4	27.8					
	S03	3	50	61	17.4	23.4	25.2	26.6	27.7	28.6	29.4	30.2	30.8	31.3	31.8					
Water-Based Epoxy	S04	3	50	62	13	18.3	18.8	19.1	19.3	19.4	19.5	19.6	19.7	19.7	19.8	1.5	1.1			
	S04	9	50	70	14.3	16.9	17.4	17.5	17.6	17.7	17.7	17.7	17.8	17.8	17.8					
	S05	3	50	63	15	17.5	18	18.2	18.3	18.4	18.5	18.6	18.6	18.6	18.7					
	S05	9	50	65	16	18.1	18.3	18.5	18.6	18.6	18.7	18.8	18.8	18.9	18.9					
Solvent-Based Epoxy	S07	3	50	65	14.4	15.9	16.2	16.4	16.5	16.6	16.7	16.7	16.8	16.8	16.8	0.9	1.15			
	S07	9	50	65	13	15.7	16	16.2	16.3	16.3	16.4	16.5	16.5	16.6	16.6					
	S08	9	50	65	14.3	17.5	18	18.3	18.5	18.5	18.6	18.6	18.7	18.7	18.8					
	S08	3	50	65	16.1	18.5	19.1	19.3	19.5	19.7	19.8	19.9	20	20.2	20.2					
Silane	S09	3	50	65	13.8	15.6	15.9	16	16.2	16.3	16.3	16.4	16.4	16.5	16.5	0.9	0.87			
	S09	9	50	65	16	19.1	19.5	19.8	19.9	20	20.1	20.1	20.2	20.2	20.3					
	S10	3	50	65	15	17.6	18	18.1	18.1	18.2	18.3	18.3	18.4	18.4	18.4					
	S11	3	50	65	16.2	18.1	18.4	18.5	18.6	18.7	18.8	18.8	18.9	18.9	19					
Siloxane	S12	3	50	65	16.1	18.3	18.6	18.7	18.8	18.9	18.9	19	19	19.1	19.2	0.9	0.57			
	S13	3	50	65	15.4	17.9	18.1	18.2	18.2	18.3	18.3	18.3	18.3	18.3	18.3					
	S14	3	50	70	13.5	15.4	15.5	15.5	15.6	15.6	15.6	15.6	15.6	15.7	15.7					
	S15	3	50	70	14.7	17.7	18.1	18.3	18.4	18.5	18.5	18.6	18.6	18.7	18.7					

Table A3 Surface Absorption Test Data for Slabs - Day 158

Treatment	Sample	Location	Day	Temperature	Column Height Reading (cm)													10min-1min	Treatment Average
					00:00	01:00	02:00	03:00	04:00	05:00	06:00	07:00	08:00	09:00	10:00				
Control	S01	5	158	70	16.2	18.1	18.5	18.8	18.9	19	19	19	19	19.1	19.1	19.1	1	2.27	
	S02	5	158	70	14.9	18	18.7	19.1	19.5	19.7	19.9	20.1	20.3	20.5	20.8	2.8			
	S03	5	158	70	15.3	17.9	18.6	19	19.2	19.5	19.7	20	20.3	20.6	20.9	3			
Water-Based Epoxy	S04	5	158	70	17.2	18.2	18.3	18.4	18.4	18.4	18.4	18.4	18.4	18.4	18.4	18.4	*	0.23	
	S05	5	158	70	14.5	16.1	16.4	16.5	16.5	16.6	16.6	16.6	16.6	16.6	16.6	16.6	*		
	S06	5	158	70	13.9	15.1	15.1	15.1	15.1	15.1	15.1	15.1	15.1	15.1	15.1	15.1	0		
Solvent-Based Epoxy	S07	5	158	75	15.4	16.2	16.2	16.2	16.2	16.2	16.2	16.1	16	16	16	16	-0.2	-0.35	
	S08	5	158	75	17.1	18	18.1	18.1	18.2	18.2	18.2	18.2	18.2	18.2	18.2	18.2	0.2		
	S09	5	158	80	15	15.7	15.7	15.6	15.5	15.4	15.4	15.3	15.2	15.2	15.1	15.1	-0.6		
Silane	S09	5	158	75	13.4	14.1	14.1	14.1	13.9	13.8	13.7	13.6	13.5	13.4	13.3	13.3	-0.8	1	
	S10	5	158	75	14.3	15.4	15.5	15.6	15.7	15.7	15.7	15.7	15.7	15.7	15.7	15.7	0.3		
	S11	5	158	80	12.9	14.1	14.6	14.9	15.3	15.5	15.7	15.9	16.2	16.4	16.5	16.5	2.4		
Siloxane	S12	5	158	80	16.1	17.4	17.5	17.6	17.6	17.7	17.7	17.7	17.7	17.7	17.7	17.7	0.3	0.67	
	S13	5	158	80	15.3	16.8	17.2	17.3	17.4	17.5	17.6	17.7	17.7	17.8	17.8	17.8	1		
	S14	5	158	80	14.9	16	16.2	16.3	16.3	16.4	16.4	16.4	16.5	16.5	16.5	16.5	0.5		
	S15	5	158	80	15.5	16.4	16.6	16.7	16.7	16.8	16.8	16.8	16.8	16.9	16.9	16.9	0.5		

* Indicates that the meniscus in the capillary tube disappeared at some point during the measurement.

Table A4 Surface Absorption Test Data for Slabs - Day 215

Treatment	Sample	Location	Day	Temperature	Column Height Reading (cm)														10min- 1min	Treatment Average
					00:00	01:00	02:00	03:00	04:00	05:00	06:00	07:00	08:00	09:00	10:00					
					16.2	18.1	18.6	18.9	19.1	19.3	19.4	19.5	19.6	19.7	19.7					
Control	S03	5	215	65	16.2	18.1	18.6	18.9	19.1	19.3	19.4	19.5	19.6	19.7	19.7	1.6	1.6			
Water-Based	S05	5	215	65	14.2	15.2	15.4	15.5	15.5	115.6	15.7	15.8	16	16.1	16.3	1.1	0.8			
	S06	5	215	65	12.8	13.9	14	14.1	14.2	14.2	14.2	14.3	14.3	14.4	14.4	0.5				
Solvent-Based Epoxy Silane	S07	5	215	70	14.2	15.3	15.4	15.4	15.4	15.4	15.5	15.5	15.5	15.5	15.5	0.2	*			
	S08	5	215	70	14.2	15.8	16.3	16.4	16.5	16.5	16.5	16.5	16.5	16.5	16.5	0.7	*			
	S09	5	215	70	14.6	15.3	15.3	15.3	15.3	15.3	15.3	15.2	15.2	15.2	15.2	-0.1	*			
Silane	S10	5	215	70	15.4	16.5	16.6	16.6	16.6	16.6	16.6	16.6	16.6	16.6	16.5	0	*			
	S11	5	215	70	16.9	18.3	18.5	18.6	18.6	18.6	18.6	18.6	18.6	18.6	18.6	0.3	*			

* Indicates that the meniscus in the capillary tube disappeared at some point during the measurement.

Table A5 Surface Absorption Test Data for Slabs - Day 292

Treatment	Sample	Location	Day	Temperature	Column Height Reading (cm)														10min-1min	Treatment Average
					00:00	01:00	02:00	03:00	04:00	05:00	06:00	07:00	08:00	09:00	10:00					
Control	S01	5	292	70	15.4	16.4	16.9	17.2	17.4	17.7	17.9	18.1	18.2	18.4	18.5	2.1	1.85			
	S02	5	292	70	14.8	15.8	16.2	16.4	16.6	16.8	17	17.1	17.2	17.3	17.4	1.6				
Solvent-Based	S07	5	292	75	15.1	15.9	16.3	16.5	16.8	17	17.1	17.3	17.5	17.7	17.8	1.9	2			
	S08	5	292	75	13.2	14.1	14.5	14.8	15.1	15.3	15.5	15.7	15.9	16.1	16.2	2.1				
Silane	S10	5	292	75	15.1	16.1	16.5	16.6	16.8	16.9	17	17.1	17.2	17.3	17.3	1.2	1.43			
	S11	5	292	75	12.8	13.9	14.3	14.5	14.7	14.9	15	15.2	15.3	15.4	15.5	1.6				
	S12	5	292	75	12.8	14.2	14.6	14.8	14.9	15	15.2	15.3	15.4	15.6	15.7	1.5				
Siloxane	S13	5	292	80	13.8	14.7	15	15.1	15.2	15.3	15.4	15.4	15.5	15.5	15.6	0.9	0.97			
	S14	5	292	80	14.6	15.9	16.1	16.3	16.4	16.5	16.6	16.7	16.7	16.8	16.9	1				
	S15	5	292	80	15.3	17	17.2	17.4	17.5	17.6	17.7	17.8	17.9	17.9	18	1				

Table A6 Surface Absorption Test Data for I-81 Bridge

Treatment and Region	Location	Day	Temperature	Column Height Reading (cm)												10min-1min	Treatment Average	
				00:00	01:00	02:00	03:00	04:00	05:00	06:00	07:00	08:00	09:00	10:00				
Control Wheel Path	LWP	261	65	13	14.1	14.6	14.9	15.1	15.2	15.4	15.5	15.6	15.7	15.8	15.8	15.8	1.7	1.5
	RWPA	261	71	13.5	14.5	14.9	15.2	15.3	15.4	15.5	15.6	15.7	15.7	15.8	15.8	15.8	1.3	
	RWPB	261	70	12.3	13.7	14.1	14.4	14.6	14.8	14.9	15	15.1	15.1	15.2	15.2	15.2	1.5	
Control Shoulder	SH1	261	70	13.3	14.5	14.9	15.2	15.4	15.5	15.6	15.7	15.8	15.9	16	16	16	1.5	1.3
	SH2	261	73	12.4	13.2	13.5	13.6	13.7	13.8	13.9	13.9	14	14	14.1	14.1	14.1	0.9	
	SH3	261	68	13.4	14.4	14.9	15.2	15.4	15.5	15.6	15.7	15.8	15.9	15.9	15.9	15.9	1.5	
SBE Wheel Path	LWP	261	65	13.3	14.2	14.6	14.8	15.1	15.2	15.4	15.4	15.6	15.7	15.8	15.8	15.8	1.6	1.1
	RWPA	261	73	14.7	15	15.2	15.3	15.4	15.5	15.5	15.6	15.7	15.7	15.8	15.8	15.8	0.8	
	RWPB	261	70	12.4	13	13.2	13.3	13.4	13.5	13.5	13.6	13.7	13.8	13.9	13.9	13.9	0.9	
SBE Shoulder	SH1	261	70	12.9	13.6	13.9	14	14.4	14.2	14.3	14.3	14.4	14.4	14.4	14.4	14.4	0.8	0.83
	SH2	261	73	13.4	13.9	14.1	14.2	14.4	14.4	14.5	14.5	14.6	14.6	14.7	14.7	14.7	0.8	
	SH3	261	68	13.3	14	14.3	14.5	14.6	14.7	14.7	14.8	14.8	14.9	14.9	14.9	14.9	0.9	
Silane Wheel Path	LWP	261	65	13.6	15	15.4	15.7	15.9	16	16.1	16.2	16.3	16.4	16.5	16.5	16.5	1.5	1.63
	RWPA	261	74	12.4	13.9	14.4	14.8	15.1	15.3	15.4	15.6	15.7	15.8	15.9	15.9	15.9	2	
	RWPB	261	70	12.3	14	14.4	14.7	14.9	15	15.1	15.2	15.3	15.4	15.4	15.4	15.4	1.4	
Silane Shoulder	SH1	261	70	13.7	14.6	14.9	15.1	15.2	15.3	15.4	15.4	15.5	15.5	15.6	15.6	15.6	1	1.3
	SH2	261	73	12.8	13.7	14.1	14.4	14.8	15	15.2	15.4	15.6	15.7	15.7	15.7	15.7	2	
	SH3	261	68	12.9	13.6	13.8	14	14.1	14.2	14.3	14.4	14.4	14.5	14.5	14.5	14.5	0.9	
Siloxane Wheel Path	LWP	261	65	12.8	13.9	14.3	14.5	14.7	14.8	14.9	14.9	15	15.1	15.1	15.1	15.1	1.2	1.27
	RWPA	261	75	12.8	13.3	13.8	14	14.2	14.3	14.4	14.4	14.4	14.5	14.5	14.5	14.5	1.2	
	RWPB	261	70	12.3	13.4	13.8	14.1	14.2	14.4	14.5	14.6	14.7	14.7	14.8	14.8	14.8	1.4	
Siloxane Shoulder	SH1	261	70	12	13.2	13.7	13.9	14.1	14.2	14.3	14.3	14.4	14.4	14.5	14.5	14.5	1.3	0.9
	SH2	261	73	12.6	13.4	13.6	13.7	13.8	13.9	13.9	14	14.1	14.1	14.2	14.2	14.2	0.8	
	SH3	261	68	12.8	13.8	14.1	14.2	14.3	14.4	14.4	14.4	14.4	14.4	14.4	14.4	14.4	0.6	
WBE Wheel Path	LWP	261	65	13.3	14.5	15.1	15.4	15.6	15.8	15.9	16.1	16.2	16.3	16.4	16.4	16.4	1.9	1.33
	RWPA	261	72	13.7	14.4	14.6	14.8	15	15.1	15.1	15.2	15.2	15.3	15.3	15.3	15.3	0.9	
	RWPB	261	70	12.4	13.1	13.4	13.6	13.8	13.9	14	14.1	14.2	14.2	14.2	14.3	14.3	1.2	
WBE Shoulder	SH1	261	70	13.4	14.2	14.6	14.9	15.1	15.2	15.3	15.3	15.4	15.5	15.6	15.6	15.6	1.4	1.03
	SH2	261	73	13.1	13.7	13.9	14	14	14.1	14.2	14.2	14.3	14.3	14.4	14.4	14.4	0.7	
	SH3	261	68	12.6	13.8	14.1	14.3	14.4	14.5	14.5	14.6	14.7	14.7	14.8	14.8	14.8	1	

Table A7 Surface Absorption Test Data for Pepper's Ferry Bridge

Treatment and Region	Location	Day	Temperature	Column Height Reading (cm)																10min-1min	Treatment Average
				00:00	01:00	02:00	03:00	04:00	05:00	06:00	07:00	08:00	09:00	10:00							
				00:00	01:00	02:00	03:00	04:00	05:00	06:00	07:00	08:00	09:00	10:00							
Control Wheel Path	LWPA	273	65	12.6	13.3	13.5	13.8	13.9	14	14.1	14.2	14.3	14.4	14.5	14.6	14.7	14.8	14.9	15.2	1.2	1.03
	RWP	273	80	13.3	13.9	14.1	14.3	14.4	14.5	14.6	14.7	14.8	14.9	15.0	15.1	15.2	15.3	15.4	15.5	1	
	RWPA	273	65	13	13.8	14	14.2	14.3	14.4	14.5	14.6	14.7	14.8	14.9	15.0	15.1	15.2	15.3	15.4	0.9	
Control Shoulder	SH1	273	80	14.1	14.8	15	15.2	15.4	15.5	15.6	15.7	15.8	15.9	16	16.1	16.2	16.3	16.4	16.5	1.2	1.4
	SH2	273	75	12.4	13.2	13.5	13.8	14	14.2	14.4	14.6	14.8	15	15.2	15.4	15.6	15.8	16	16.2	2	
	SH3	273	60	13.4	13.8	14	14.2	14.3	14.4	14.5	14.6	14.7	14.8	14.9	15.0	15.1	15.2	15.3	15.4	1	
SBE Wheel Path	LWPA	273	65	12.4	13	13.4	13.7	14	14.2	14.4	14.5	14.6	14.7	14.8	14.9	15.0	15.1	15.2	15.3	1.7	1.17
	RWP	273	80	12.8	13.5	13.8	14	14.1	14.2	14.3	14.4	14.5	14.6	14.7	14.8	14.9	15.0	15.1	15.2	1	
	RWPA	273	65	12.4	13.8	14	14.1	14.2	14.3	14.4	14.5	14.6	14.7	14.8	14.9	15.0	15.1	15.2	15.3	0.8	
SBE Shoulder	SH1	273	80	13	14.1	14.5	14.8	15	15.2	15.3	15.4	15.5	15.6	15.7	15.8	15.9	16	16.1	16.2	1.6	1.13
	SH2	273	75	13.7	14.3	14.5	14.7	14.8	14.8	14.9	15	15.1	15.2	15.3	15.4	15.5	15.6	15.7	15.8	0.9	
	SH3	273	60	13.3	13.8	14	14.2	14.3	14.4	14.4	14.5	14.6	14.7	14.8	14.9	15.0	15.1	15.2	15.3	0.9	
Silane Wheel Path	LWPA	273	65	12.7	13.4	13.6	13.7	13.8	13.9	13.9	14	14	14	14	14	14	14	14	14	0.7	1.47
	RWP	273	80	13.1	14.3	14.9	15.3	15.6	15.9	16.1	16.3	16.4	16.5	16.6	16.7	16.8	16.9	17	17.1	2.3	
	RWPA	273	65	13.8	14.7	15.2	15.4	15.6	15.7	15.8	15.9	16	16.1	16.2	16.3	16.4	16.5	16.6	16.7	1.4	
Silane Shoulder	SH1	273	80	12.5	13.9	14.2	LEAK	LEAK	LEAK	15.3	15.6	15.9	16.4	LEAK	LEAK	LEAK	LEAK	LEAK	LEAK	NA	1.1
	SH2	273	75	13.7	14.4	14.8	15.1	15.3	15.6	15.9	16.2	16.5	16.8	17.1	17.4	17.7	18	18.3	18.6	NA	
	SH3	273	60	13.2	14	14.3	14.5	14.6	14.7	14.8	14.9	15	15.1	15.2	15.3	15.4	15.5	15.6	15.7	1.1	
Siloxane Wheel Path	LWPA	273	65	12.5	13.3	13.6	13.8	13.9	13.9	14	14	14	14	14	14	14	14	14	14	0.9	0.9
	RWP	273	80	12.8	13.8	14.1	14.3	14.4	14.4	14.4	14.5	14.6	14.7	14.8	14.9	15	15.1	15.2	15.3	0.7	
	RWPA	273	65	12.3	13.3	13.6	13.8	13.9	14	14.1	14.2	14.3	14.4	14.5	14.6	14.7	14.8	14.9	15	1.1	
Siloxane Shoulder	SH1	273	80	13.1	14.2	14.6	14.8	14.9	14.9	15	15	15	15	15	15	15	15	15	15	0.9	0.83
	SH2	273	75	12.6	13.6	14	14.1	14.1	14.2	14.2	14.2	14.2	14.2	14.2	14.2	14.2	14.2	14.2	14.2	0.7	
	SH3	273	60	12.7	13.6	13.9	14.1	14.2	14.3	14.3	14.3	14.4	14.4	14.4	14.4	14.4	14.4	14.4	14.4	0.9	
WBE Wheel Path	LWPA	273	65	12.5	13.7	14.1	14.4	14.6	14.8	14.9	15	15	15	15	15	15	15	15	15	1.7	1.47
	RWP	273	80	12.8	14.2	14.7	15.2	15.5	15.6	15.7	15.7	15.7	15.7	15.8	15.8	15.8	15.8	15.8	15.8	1.6	
	RWPA	273	65	12.2	12.8	13	13.2	13.4	13.5	13.6	13.7	13.8	13.8	13.8	13.8	13.8	13.8	13.8	13.8	1.1	
WBE Shoulder	SH1	273	80	11.2	12.1	12.4	12.6	12.8	12.9	13	13.1	13.2	13.3	13.4	13.4	13.4	13.4	13.4	13.4	1.3	1.3
	SH2	273	75	13.2	14.1	14.6	14.9	15.1	15.3	15.4	15.5	15.6	15.7	15.8	15.9	16	16.1	16.2	16.3	1.7	
	SH3	273	60	12.5	13.3	13.5	13.7	13.8	13.9	14	14	14	14	14	14	14	14	14	14	0.9	

Appendix B

Chloride Content Data

**Table B1 Background Chloride Content: Before Salt
Water Application**

Specimen	Titrant Needed to Balance (ml)	
S2	0.61	
S3	0.86	
S8	0.73	Normality of Silver
W5	0.87	Nitrate Solution = 0.0474
W1	0.78	
S10	0.81	Weight of Sample 10.0 g
W2	0.73	
W3	0.78	
W4	1.03	$Cl\% = 3.5454(0.80)(0.0474)/10.0$
Avg Vol	0.8	$Cl\% = 0.01344\%$
Std Dev	0.1096	
COV	0.14	
<div style="border: 1px solid black; padding: 5px; display: inline-block;"> Chloride Content = 0.54 lb/cu yd </div>		
without outliers S2 and W4		
Avg Vol	0.79	
Std Dev	0.0521	
COV	0.07	

Table B2 Chloride Content: Control Slabs - Week 10

		CONTROL				
	Specimen	Location	mV	%Cl/VPI	%Cl/ADJ	lb/cu yd
WEEK 10 DEPTH 1	S1	3	84.3	0.030659	0.049874	1.952556
	S1	7	84.7	0.02965	0.048713	1.907107
	S1	11	88.7	0.020443	0.038115	1.492185
	S2	3	76.5	0.05412	0.076878	3.009787
	S2	7	76.9	0.052721	0.075268	2.94675
	S2	11	81.5	0.038213	0.058569	2.292976
	S3	3	73.2	0.066601	0.091245	3.572238
	S3	7	83.1	0.033788	0.053476	2.093571
	S3	11	86.6	0.025084	0.043457	1.701333
					Average	
					CTL-10-1=	2.33
Std dev = 0.694746					CoeffVar=	0.298
		CONTROL				
	Specimen	Location	mV	%Cl/VPI	%Cl/ADJ	lb/cu yd
WEEK 10 DEPTH 2	S1	3	100.5	0.000764	0.015464	0.605405
	S1	7	97.3	0.005178	0.020545	0.804321
	S1	11	105	-0.00452	0.00938	0.367212
	S2	3	98.4	0.003594	0.018721	0.732913
	S2	7	98.3	0.003735	0.018883	0.739269
	S2	11	95.8	0.007461	0.023171	0.90716
	S3	3	98.6	0.003313	0.018398	0.72028
	S3	7	99.1	0.002623	0.017603	0.689157
	S3	11	102.1	-0.00123	0.013168	0.515521
					Average	
					CTL-10-2=	0.68
Std dev = 0.16022					CoeffVar=	0.236
		CONTROL				
	Specimen	Location	mV	%Cl/VPI	%Cl/ADJ	lb/cu yd
WEEK 10 DEPTH 3	S1	3	103.8	-0.00321	0.010891	0.426402
	S1	7	105.3	-0.00484	0.009013	0.352874
	S1	11	101.7	-0.00074	0.013727	0.53743
	S2	3	102.9	-0.00218	0.012076	0.47279
	S2	7	102.8	-0.00206	0.012211	0.478054
	S2	11	101.5	-0.0005	0.014011	0.548523
	S3	3	100.4	0.000893	0.015612	0.611226
	S3	7	105.3	-0.00484	0.009013	0.352874
	S3	11	100.2	0.001153	0.015912	0.62294
					Average	
					CTL-10-3=	0.49
Std dev = 0.10008					CoeffVar=	0.204

Table B3 Chloride Content: Control Slabs - Week 20

		CONTROL				
	Specimen	Location	mV	%Cl/VPI	%Cl/ADJ	lb/cu yd
WEEK 20 DEPTH 1	S1	1	80.3	0.041732	0.06262	2.451561
	S1	4	74.8	0.060334	0.084031	3.289811
	S1	8	67.4	0.093194	0.121855	4.770614
	S2	1	76.5	0.05412	0.076878	3.009787
	S2	4	67.3	0.093712	0.122451	4.793939
	S2	8	70.2	0.079548	0.106148	4.155689
	S3	1	69	0.085201	0.112654	4.410414
	S3	4	65.7	0.102295	0.132331	5.180758
	S3	8	67.3	0.093712	0.122451	4.793939
					Average	
					CTL-20-1=	4.1
Std dev = 0.951475					CoeffVar=	0.232
		CONTROL				
	Specimen	Location	mV	%Cl/VPI	%Cl/ADJ	lb/cu yd
WEEK 20 DEPTH 2	S1	1	104.4	-0.00387	0.010126	0.396434
	S1	4	102	-0.00111	0.013307	0.520964
	S1	8	101.6	-0.00062	0.013869	0.542965
	S2	1	104.1	-0.00354	0.010506	0.411324
	S2	4	97.4	0.005031	0.020375	0.797693
	S2	8	100.7	0.000508	0.015168	0.593837
	S3	1	97.9	0.004305	0.019539	0.764963
	S3	4	96.3	0.006684	0.022277	0.872159
	S3	8	100.3	0.001023	0.015762	0.617071
					Average	
					CTL-20-2	0.61
Std dev = 0.167966					CoeffVar=	0.275
		CONTROL				
	Specimen	Location	mV	%Cl/VPI	%Cl/ADJ	lb/cu yd
WEEK 20 DEPTH 3	S1	1	104.8	-0.00168	0.012655	0.49544
	S1	4	104.3	-0.00107	0.013351	0.522708
	S1	8	105.9	-0.00296	0.011174	0.437443
	S2	1	106.3	-0.00342	0.010652	0.417014
	S2	4	104.3	-0.00107	0.013351	0.522708
	S2	8	104.6	-0.00144	0.012932	0.506278
	S3	1	105.1	-0.00203	0.012244	0.479354
	S3	4	105.1	-0.00203	0.012244	0.479354
	S3	8	105.2	-0.00215	0.012108	0.474037
					Average	
					CTL-20-3	0.48
Std dev = 0.036001					CoeffVar=	0.075

Table B4 Chloride Content: Control Slabs - Week 30

		CONTROL				
	Specimen	Location	mV	%Cl/VPI	%Cl/ADJ	lb/cu yd
WEEK 30 DEPTH 1	S1	2	64.6	0.112541	0.144124	5.642462
	S1	5	56	0.177229	0.218583	8.557534
	S1	10	57.6	0.163293	0.202542	7.92951
	S2	2	61	0.136712	0.171946	6.731683
	S2	5	61.1	0.135988	0.171113	6.699066
	S2	10	55.9	0.178133	0.219623	8.598256
	S3	2	65.2	0.108868	0.139896	5.476945
	S3	5	62.6	0.125501	0.159041	6.226467
	S3	10	52.6	0.210271	0.256616	10.04653
					Average	
					CTL-30-1=	7.32
Std dev = 1.545529					CoeffVar=	0.211
		CONTROL				
	Specimen	Location	mV	%Cl/VPI	%Cl/ADJ	lb/cu yd
WEEK 30 DEPTH 2	S1	2	90.6	0.015997	0.032998	1.291867
	S1	5	84.4	0.030235	0.049386	1.933446
	S1	10	88.4	0.020616	0.038314	1.499995
	S2	2	91.7	0.013849	0.030525	1.195042
	S2	5	95.9	0.006529	0.022099	0.865185
	S2	10	89.8	0.017626	0.034872	1.365255
	S3	2	90	0.017214	0.034398	1.346668
	S3	5	91.6	0.01404	0.030745	1.203654
	S3	10	80.3	0.041995	0.062922	2.463397
					Average	
					CTL-30-2	1.46
Std dev = 0.470678					CoeffVar=	0.322
		CONTROL				
	Specimen	Location	mV	%Cl/VPI	%Cl/ADJ	lb/cu yd
WEEK 30 DEPTH 3	S1	2	104.9	-0.0053	0.008484	0.33216
	S1	5	104.7	-0.00508	0.008733	0.341879
	S1	10	103.7	-0.00398	0.010007	0.391761
	S2	2	105	-0.00541	0.008361	0.327332
	S2	5	104.5	-0.00487	0.008983	0.351682
	S2	10	103.4	-0.00364	0.0104	0.407154
	S3	2	103.4	-0.00364	0.0104	0.407154
	S3	5	103.9	-0.0042	0.009747	0.38161
	S3	10	104.2	-0.00454	0.009363	0.366548
					Average	
					CTL-30-3	0.37
Std dev = 0.031029					CoeffVar=	0.084

**Table B5 Chloride Content: Water-Based Epoxy on Slabs -
Week 10**

		WATER-BASED EPOXY				
	Specimen	Location	mV	%Cl/VPI	%Cl/ADJ	lb/cu yd
WEEK 10 DEPTH 1	S4	3	81.4	0.0385	0.058899	2.305889
	S4	7	84.1	0.031169	0.050462	1.975569
	S4	11	89.6	0.018575	0.035965	1.408038
	S5	3	89.7	0.018372	0.035731	1.398882
	S5	7	90.5	0.016777	0.033895	1.327007
	S5	11	92.7	0.012657	0.029153	1.141343
	S6	3	89.8	0.01817	0.035498	1.389765
	S6	7	81.7	0.037644	0.057913	2.267313
	S6	11	90.5	0.016777	0.033895	1.327007
					Average	
					WBE-10-1	1.62
Std dev = 0.442062					CoeffVar=	0.273
		WATER-BASED EPOXY				
	Specimen	Location	mV	%Cl/VPI	%Cl/ADJ	lb/cu yd
WEEK 10 DEPTH 2	S4	3	98.4	0.003594	0.018721	0.732913
	S4	7	99.5	0.002081	0.016979	0.664724
	S4	11	101.6	-0.00062	0.013869	0.542965
	S5	3	99.5	0.002081	0.016979	0.664724
	S5	7	98.6	0.003313	0.018398	0.72028
	S5	11	102.9	-0.00218	0.012076	0.47279
	S6	3	96.8	0.005923	0.021402	0.837885
	S6	7	98.3	0.003735	0.018883	0.739269
	S6	11	101.4	-0.00037	0.014153	0.554104
					Average	
					WBE-10-2	0.66
Std dev = 0.115579					CoeffVar=	0.175
		WATER-BASED EPOXY				
	Specimen	Location	mV	%Cl/VPI	%Cl/ADJ	lb/cu yd
WEEK 10 DEPTH 3	S4	3	103.1	-0.00241	0.011809	0.46233
	S4	7	104.2	-0.00365	0.010379	0.40634
	S4	11	103.3	-0.00264	0.011544	0.451957
	S5	3	103.7	-0.0031	0.011021	0.43147
	S5	7	102.2	-0.00135	0.013029	0.510101
	S5	11	100.3	0.001023	0.015762	0.617071
	S6	3	101	0.000127	0.01473	0.576666
	S6	7	101.9	-0.00099	0.013446	0.526429
	S6	11	102.9	-0.00218	0.012076	0.47279
					Average	
					WBE-10-3	0.5
Std dev = 0.069008					CoeffVar=	0.138

**Table B6 Chloride Content: Water-Based Epoxy on Slabs -
Week 20**

		WATER-BASED EPOXY					
	Specimen	Location	mV	%Cl/VPI	%Cl/ADJ	lb/cu yd	
WEEK 20	S4	1	74	0.063415	0.087577	3.428656	
	S4	4	76.2	0.055184	0.078104	3.057763	
	S4	8	74.3	0.062247	0.086234	3.376042	
	DEPTH	S5	1	78.5	0.047354	0.069091	2.704916
		S5	4	73.3	0.066197	0.09078	3.554026
		S5	8	76.1	0.055542	0.078516	3.07389
	1	S6	1	78.9	0.046068	0.06761	2.64695
		S6	4	70.8	0.076827	0.103015	4.033053
		S6	8	77.4	0.051005	0.073293	2.869426
					Average		
					WBE-20-1	3.19	
Std dev = 0.447023					CoeffVar=	0.14	
		WATER-BASED EPOXY					
	Specimen	Location	mV	%Cl/VPI	%Cl/ADJ	lb/cu yd	
WEEK 20	S4	1	104.1	-0.00354	0.010506	0.411324	
	S4	4	104	-0.00343	0.010634	0.416329	
	S4	8	104	-0.00343	0.010634	0.416329	
	DEPTH	S5	1	104.1	-0.00354	0.010506	0.411324
		S5	4	100.7	0.000508	0.015168	0.593837
		S5	8	104.3	-0.00376	0.010252	0.401377
	2	S6	1	97.5	0.004885	0.020207	0.791092
		S6	4	100.8	0.00038	0.015021	0.588089
		S6	8	103.5	-0.00287	0.011281	0.44167
					Average		
					WBE-20-2	0.5	
Std dev = 0.134195					CoeffVar=	0.268	
		WATER-BASED EPOXY					
	Specimen	Location	mV	%Cl/VPI	%Cl/ADJ	lb/cu yd	
WEEK 20	S4	1	105	-0.00191	0.01238	0.484693	
	S4	4	104.3	-0.00107	0.013351	0.522708	
	S4	8	105.8	-0.00285	0.011305	0.442604	
	DEPTH	S5	1	105.1	-0.00203	0.012244	0.479354
		S5	4	104.7	-0.00156	0.012793	0.500847
		S5	8	104.1	-0.00083	0.013634	0.533778
	3	S6	1	103.5	-7.6E-05	0.014497	0.567555
		S6	4	104.9	-0.0018	0.012517	0.490055
		S6	8	105.5	-0.0025	0.011704	0.458221
					Average		
					WBE-20-3	0.5	
Std dev = 0.038689					CoeffVar=	0.077	

**Table B7 Chloride Content: Water-Based Epoxy on Slabs -
Week 30**

		WATER-BASED EPOXY				
	Specimen	Location	mV	%Cl/VPI	%Cl/ADJ	lb/cu yd
WEEK 30 DEPTH 1	S4	2	67.1	0.09785	0.127214	4.980431
	S4	5	59.5	0.147956	0.184888	7.238361
	S4	10	56.9	0.169271	0.209423	8.198898
	S5	52	62.8	0.124153	0.15749	6.165753
	S5	5	58.7	0.154259	0.192144	7.522422
	S5	10	59.4	0.148732	0.185781	7.27333
	S6	2	63.8	0.11759	0.149936	5.869983
	S6	5	62.3	0.127544	0.161393	6.318535
	S6	10	58.9	0.152663	0.190306	7.450477
					Average	
					WBE-30-1	6.78
Std dev = 1.007739					CoeffVar=	0.149
		WATER-BASED EPOXY				
	Specimen	Location	mV	%Cl/VPI	%Cl/ADJ	lb/cu yd
WEEK 30 DEPTH 2	S4	2	90.2	0.016805	0.033927	1.328242
	S4	5	89.6	0.018042	0.035351	1.384005
	S4	10	91	0.015204	0.032085	1.256121
	S5	2	92.8	0.011801	0.028167	1.102742
	S5	5	93.7	0.010196	0.02632	1.030442
	S5	10	91.8	0.013659	0.030306	1.186467
	S6	2	95.7	0.006848	0.022466	0.879563
	S6	5	81.5	0.038333	0.058707	2.298386
	S6	10	93.2	0.01108	0.027337	1.070259
					Average	
					WBE-30-2	1.28
Std dev = 0.411944					CoeffVar=	0.322
		WATER-BASED EPOXY				
	Specimen	Location	mV	%Cl/VPI	%Cl/ADJ	lb/cu yd
WEEK 30 DEPTH 3	S4	2	102.5	-0.00258	0.011611	0.454557
	S4	5	105.2	-0.00562	0.008116	0.31774
	S4	10	101	-0.00074	0.013737	0.537808
	S5	2	104	-0.00431	0.009619	0.376568
	S5	5	106.2	-0.00666	0.006922	0.27101
	S5	10	103.5	-0.00375	0.010268	0.402001
	S6	2	102.2	-0.00222	0.012025	0.470775
	S6	5	100.5	-9.3E-05	0.014477	0.566787
	S6	10	104.4	-0.00476	0.009109	0.356616
					Average	
					WBE-30-3	0.42
Std dev = 0.098745					CoeffVar=	0.235

Table B8 Chloride Content: Solvent-Based Epoxy on Slabs -
Week 10

SOLVENT-BASED EPOXY						
	Specimen	Location	mV	%Cl/VPI	%Cl/ADJ	lb/cu yd
WEEK	S7	3	83.1	0.033788	0.053476	2.093571
	S7	7	83.9	0.031684	0.051054	1.998775
	S7	11	87.9	0.022163	0.040094	1.569697
10	S8	3	79.7	0.043559	0.064723	2.533896
	S8	7	83.2	0.033521	0.053168	2.081547
	S8	11	80.1	0.042336	0.063315	2.478776
DEPTH	S9	3	84.3	0.030659	0.049874	1.952556
	S9	7	86.8	0.024624	0.042927	1.680611
	S9	11	78.5	0.047354	0.069091	2.704916
					Average	
					SBE-10-1	2.12
Std dev =			0.384535	CoeffVar=	0.181	
SOLVENT-BASED EPOXY						
	Specimen	Location	mV	%Cl/VPI	%Cl/ADJ	lb/cu yd
WEEK	S7	3	100.8	0.00038	0.015021	0.588089
	S7	7	98.8	0.003035	0.018078	0.707752
	S7	11	101	0.000127	0.01473	0.576666
10	S8	3	97.8	0.004449	0.019705	0.771454
	S8	7	99.3	0.002351	0.01729	0.676889
	S8	11	98.6	0.003313	0.018398	0.72028
DEPTH	S9	3	97.8	0.004449	0.019705	0.771454
	S9	7	99	0.00276	0.017761	0.695329
	S9	11	98.3	0.003735	0.018883	0.739269
					Average	
					SBE-10-2	0.69
Std dev =			0.070893	CoeffVar=	0.103	
SOLVENT-BASED EPOXY						
	Specimen	Location	mV	%Cl/VPI	%Cl/ADJ	lb/cu yd
WEEK	S7	3	103.7	-0.0031	0.011021	0.43147
	S7	7	103.5	-0.00287	0.011281	0.44167
	S7	11	101.8	-0.00087	0.013587	0.531918
10	S8	3	102.5	-0.00171	0.012618	0.493976
	S8	7	102.3	-0.00147	0.012892	0.504703
	S8	11	101	0.000127	0.01473	0.576666
DEPTH	S9	3	102.7	-0.00194	0.012346	0.483339
	S9	7	101.6	-0.00062	0.013869	0.542965
	S9	11	102.6	-0.00183	0.012481	0.488647
					Average	
					SBE-10-3	0.5
Std dev =			0.046507	CoeffVar=	0.093	

**Table B9 Chloride Content: Solvent-Based Epoxy on Slabs -
Week 20**

SOLVENT-BASED EPOXY						
	Specimen	Location	mV	%Cl/VPI	%Cl/ADJ	lb/cu yd
WEEK 20 DEPTH 1	S7	1	82.8	0.034595	0.054405	2.129947
	S7	4	72	0.071585	0.096982	3.796849
	S7	8	79.1	0.045433	0.066879	2.61833
	S8	1	71	0.075935	0.101989	3.992856
	S8	4	63.2	0.116916	0.14916	5.8396
	S8	8	70.3	0.07909	0.10562	4.135035
	S9	1	66.7	0.096863	0.126078	4.935963
	S9	4	80.1	0.042336	0.063315	2.478776
	S9	8	64.1	0.111475	0.142897	5.594422
Average						
SBE-20-1						3.95
Std dev = 1.348922						CoeffVar= 0.341
SOLVENT-BASED EPOXY						
	Specimen	Location	mV	%Cl/VPI	%Cl/ADJ	lb/cu yd
WEEK 20 DEPTH 2	S7	1	103.8	-0.00321	0.010891	0.426402
	S7	4	100.7	0.000508	0.015168	0.593837
	S7	8	102	-0.00111	0.013307	0.520964
	S8	1	98.9	0.002897	0.017919	0.701528
	S8	4	95.3	0.008254	0.024084	0.942903
	S8	8	102.9	-0.00218	0.012076	0.47279
	S9	1	94.6	0.009392	0.025395	0.994219
	S9	4	104.2	-0.00365	0.010379	0.40634
	S9	8	94.5	0.009558	0.025586	1.001673
Average						
SBE-20-2						0.67
Std dev = 0.246539						CoeffVar= 0.368
SOLVENT-BASED EPOXY						
	Specimen	Location	mV	%Cl/VPI	%Cl/ADJ	lb/cu yd
WEEK 20 DEPTH 3	S7	1	106	-0.00308	0.011042	0.432303
	S7	4	101.7	0.002291	0.017221	0.674189
	S7	8	106	-0.00308	0.011042	0.432303
	S8	1	102.9	0.000693	0.015382	0.602201
	S8	4	104.3	-0.00107	0.013351	0.522708
	S8	8	105.3	-0.00227	0.011973	0.468743
	S9	1	105.6	-0.00262	0.011571	0.452993
	S9	4	106.4	-0.00353	0.010523	0.41196
	S9	8	104	-0.0007	0.013776	0.539348
Average						
SBE-20-3						0.5
Std dev = 0.088603						CoeffVar= 0.177

**Table B10 Chloride Content: Solvent-Based Epoxy on Slabs -
Week 30**

SOLVENT-BASED EPOXY						
	Specimen	Location	mV	%Cl/VPI	%Cl/ADJ	lb/cu yd
WEEK 30 DEPTH 1	S7	2	57.3	0.165832	0.205465	8.043958
	S7	5	62.8	0.124153	0.15749	6.165753
	S7	10	61.4	0.133835	0.168635	6.602062
	S8	52	57	0.168405	0.208427	8.15991
	S8	5	58.7	0.154259	0.192144	7.522422
	S8	10	54.4	0.192171	0.235782	9.230846
	S9	2	63.8	0.11759	0.149936	5.869983
	S9	5	62.3	0.127544	0.161393	6.318535
	S9	10	58.9	0.152663	0.190306	7.450477
					Average	
					SBE-30-1	7.26
Std dev = 1.110321					CoeffVar=	0.153
SOLVENT-BASED EPOXY						
	Specimen	Location	mV	%Cl/VPI	%Cl/ADJ	lb/cu yd
WEEK 30 DEPTH 2	S7	2	85.2	0.028175	0.047014	1.840617
	S7	5	93.1	0.011259	0.027543	1.078327
	S7	10	92.5	0.01235	0.028799	1.127478
	S8	2	89.4	0.018462	0.035834	1.402918
	S8	5	85.8	0.026676	0.04529	1.773085
	S8	10	84.5	0.029973	0.049085	1.921664
	S9	2	94	0.009675	0.025721	1.006965
	S9	5	94.7	0.008486	0.024351	0.953361
	S9	10	92.1	0.013093	0.029654	1.160966
					Average	
					SBE-30-2	1.36
Std dev = 0.384363					CoeffVar=	0.283
SOLVENT-BASED EPOXY						
	Specimen	Location	mV	%Cl/VPI	%Cl/ADJ	lb/cu yd
WEEK 30 DEPTH 3	S7	2	102.6	-0.0027	0.011474	0.449198
	S7	5	104.4	-0.00476	0.009109	0.356616
	S7	10	104.1	-0.00443	0.00949	0.371547
	S8	2	102.9	-0.00306	0.011067	0.43326
	S8	5	106.2	-0.00666	0.006922	0.27101
	S8	10	102.8	-0.00294	0.011202	0.438549
	S9	2	102.7	-0.00282	0.011337	0.443862
	S9	5	102.1	-0.0021	0.012164	0.476229
	S9	10	103	-0.00317	0.010932	0.427993
					Average	
					SBE-30-3	0.41
Std dev = 0.063584					CoeffVar=	0.155

Table B11 Chloride Content: Silane on Slabs - Week 10

		SILANE				
	Specimen	Location	mV	%Cl/VPI	%Cl/ADJ	lb/cu yd
WEEK 10 DEPTH 1	S10	3	100.2	0.001153	0.015912	0.62294
	S10	7	102.8	-0.00206	0.012211	0.478054
	S10	11	103.1	-0.00241	0.011809	0.46233
	S11	3	103.3	-0.00264	0.011544	0.451957
	S11	7	102.6	-0.00183	0.012481	0.488647
	S11	11	95.6	0.007776	0.023534	0.921368
	S12	3	102.1	-0.00123	0.013168	0.515521
	S12	7	102.3	-0.00147	0.012892	0.504703
	S12	11	103.5	-0.00287	0.011281	0.44167
					Average	
					SIL-10-1=	0.54
Std dev = 0.151662					CoeffVar=	0.281
		SILANE				
	Specimen	Location	mV	%Cl/VPI	%Cl/ADJ	lb/cu yd
WEEK 10 DEPTH 2	S10	3	99.1	0.002623	0.017603	0.689157
	S10	7	99.9	0.001547	0.016365	0.640697
	S10	11	99.5	0.002081	0.016979	0.664724
	S11	3	100.8	0.00038	0.015021	0.588089
	S11	7	99.9	0.001547	0.016365	0.640697
	S11	11	103.4	-0.00276	0.011413	0.446803
	S12	3	102	-0.00111	0.013307	0.520964
	S12	7	101.7	-0.00074	0.013727	0.53743
	S12	11	100.4	0.000893	0.015612	0.611226
					Average	
					SIL-10-2=	0.59
Std dev = 0.07822					CoeffVar=	0.133
		SILANE				
	Specimen	Location	mV	%Cl/VPI	%Cl/ADJ	lb/cu yd
WEEK 10 DEPTH 3	S10	3	101.8	-0.00087	0.013587	0.531918
	S10	7	103.9	-0.00332	0.010763	0.421355
	S10	11	101.5	-0.0005	0.014011	0.548523
	S11	3	103.4	-0.00276	0.011413	0.446803
	S11	7	100.8	0.00038	0.015021	0.588089
	S11	11	100.4	0.000893	0.015612	0.611226
	S12	3	103.8	-0.00321	0.010891	0.426402
	S12	7	103.3	-0.00264	0.011544	0.451957
	S12	11	103.6	-0.00298	0.011151	0.436559
					Average	
					SIL-10-3=	0.5
Std dev = 0.074259					CoeffVar=	0.149

Table B12 Chloride Content: Silane on Slabs - Week 20

		SILANE					
	Specimen	Location	mV	%Cl/VPI	%Cl/ADJ	lb/cu yd	
WEEK 20	S10	1	101.7	-0.00074	0.013727	0.53743	
	S10	4	103.6	-0.00298	0.011151	0.436559	
	S10	8	102.9	-0.00218	0.012076	0.47279	
	DEPTH	S11	1	102.5	-0.00171	0.012618	0.493976
		S11	4	102.1	-0.00123	0.013168	0.515521
		S11	8	102.6	-0.00183	0.012481	0.488647
	1	S12	1	102	-0.00111	0.013307	0.520964
		S12	4	102.8	-0.00206	0.012211	0.478054
		S12	8	104.5	-0.00398	0.01	0.391513
					Average		
					SIL-20-1=	0.48	
Std dev =			0.045075	CoeffVar=	0.094		
		SILANE					
	Specimen	Location	mV	%Cl/VPI	%Cl/ADJ	lb/cu yd	
WEEK 20	S10	1	102.3	-0.00147	0.012892	0.504703	
	S10	4	103.9	-0.00332	0.010763	0.421355	
	S10	8	103.2	-0.00253	0.011676	0.457133	
	DEPTH	S11	1	103.1	-0.00241	0.011809	0.46233
		S11	4	103.3	-0.00264	0.011544	0.451957
		S11	8	103.2	-0.00253	0.011676	0.457133
	2	S12	1	103.8	-0.00321	0.010891	0.426402
		S12	4	104.2	-0.00365	0.010379	0.40634
		S12	8	104.2	-0.00365	0.010379	0.40634
					Average		
					SIL-20-2=	0.44	
Std dev =			0.031796	CoeffVar=	0.072		
		SILANE					
	Specimen	Location	mV	%Cl/VPI	%Cl/ADJ	lb/cu yd	
WEEK 20	S10	1	104	-0.0007	0.013776	0.539348	
	S10	4	105.3	-0.00227	0.011973	0.468743	
	S10	8	105.7	-0.00273	0.011438	0.447788	
	DEPTH	S11	1	106.8	-0.00397	0.010012	0.391959
		S11	4	105.5	-0.0025	0.011704	0.458221
		S11	8	103.2	0.000306	0.014937	0.584768
	3	S12	1	106.4	-0.00353	0.010523	0.41196
		S12	4	105.1	-0.00203	0.012244	0.479354
		S12	8	105.2	-0.00215	0.012108	0.474037
					Average		
					SIL-20-3=	0.47	
Std dev =			0.059268	CoeffVar=	0.126		

Table B13 Chloride Content: Silane on Slabs - Week 30

		SILANE					
	Specimen	Location	mV	%Cl/VPI	%Cl/ADJ	lb/cu yd	
WEEK 30	S10	2	102.5	-0.00258	0.011611	0.454557	
	S10	5	101.3	-0.00111	0.013301	0.52072	
	S10	10	99.5	0.001236	0.016007	0.626674	
	DEPTH 1	S11	52	101.8	-0.00174	0.012586	0.492732
		S11	5	101.5	-0.00137	0.013013	0.509451
		S11	10	102.3	-0.00234	0.011886	0.465346
		S12	2	104.5	-0.00487	0.008983	0.351682
		S12	5	102.7	-0.00282	0.011337	0.443862
		S12	10	101.2	-0.00099	0.013445	0.526391
					Average		
					SIL-30-1 =	0.49	
Std dev = 0.074515					CoeffVar =	0.152	
		SILANE					
	Specimen	Location	mV	%Cl/VPI	%Cl/ADJ	lb/cu yd	
WEEK 30	S10	2	101.3	-0.00111	0.013301	0.52072	
	S10	5	103.1	-0.00329	0.010798	0.422749	
	S10	10	103.8	-0.00409	0.009877	0.386675	
	DEPTH 2	S11	2	101.4	-0.00124	0.013156	0.515073
		S11	5	100.3	0.000169	0.014778	0.578557
		S11	10	103.3	-0.00352	0.010532	0.41233
		S12	2	103	-0.00317	0.010932	0.427993
		S12	5	103.8	-0.00409	0.009877	0.386675
		S12	10	102.8	-0.00294	0.011202	0.438549
					Average		
					SIL-30-2 =	0.45	
Std dev = 0.067443					CoeffVar =	0.15	
		SILANE					
	Specimen	Location	mV	%Cl/VPI	%Cl/ADJ	lb/cu yd	
WEEK 30	S10	2	106	-0.00645	0.007157	0.280194	
	S10	5	105.6	-0.00604	0.007632	0.298803	
	S10	10	103.4	-0.00364	0.0104	0.407154	
	DEPTH 3	S11	2	103.3	-0.00352	0.010532	0.41233
		S11	5	102.8	-0.00294	0.011202	0.438549
		S11	10	104.4	-0.00476	0.009109	0.356616
		S12	2	105.5	-0.00594	0.007752	0.303507
		S12	5	102.9	-0.00306	0.011067	0.43326
		S12	10	105.2	-0.00562	0.008116	0.31774
					Average		
					SIL-30-3 =	0.36	
Std dev = 0.062844					CoeffVar =	0.175	

Table B14 Chloride Content: Siloxane on Slabs - Week 10

		SILOXANE				
	Specimen	Location	mV	%Cl/VPI	%Cl/ADJ	lb/cu yd
WEEK 10 DEPTH 1	S13	3	103.5	-0.00287	0.011281	0.44167
	S13	7	102.5	-0.00171	0.012618	0.493976
	S13	11	103.9	-0.00332	0.010763	0.421355
	S14	3	101.6	-0.00062	0.013869	0.542965
	S14	7	102.7	-0.00194	0.012346	0.483339
	S14	11	105.2	-0.00473	0.009135	0.357633
	S15	3	95.1	0.008576	0.024455	0.957411
	S15	7	104.1	-0.00354	0.010506	0.411324
	S15	11	103.9	-0.00332	0.010763	0.421355
					Average	
					SLX-10-1=	0.5
Std dev =			0.1786	CoeffVar=	0.357	
		SILOXANE				
	Specimen	Location	mV	%Cl/VPI	%Cl/ADJ	lb/cu yd
WEEK 10 DEPTH 2	S13	3	101.8	-0.00087	0.013587	0.531918
	S13	7	102	-0.00111	0.013307	0.520964
	S13	11	104.4	-0.00387	0.010126	0.396434
	S14	3	101.8	-0.00087	0.013587	0.531918
	S14	7	102.3	-0.00147	0.012892	0.504703
	S14	11	103.6	-0.00298	0.011151	0.436559
	S15	3	97.5	0.004885	0.020207	0.791092
	S15	7	101.5	-0.0005	0.014011	0.548523
	S15	11	102.7	-0.00194	0.012346	0.483339
					Average	
					SLX-10-2=	0.53
Std dev =			0.110636	CoeffVar=	0.209	
		SILOXANE				
	Specimen	Location	mV	%Cl/VPI	%Cl/ADJ	lb/cu yd
WEEK 10 DEPTH 3	S13	3	104.8	-0.00431	0.009626	0.376871
	S13	7	102.1	-0.00123	0.013168	0.515521
	S13	11	101.5	-0.0005	0.014011	0.548523
	S14	3	104.6	-0.00409	0.009875	0.386612
	S14	7	100.5	0.000764	0.015464	0.605405
	S14	11	100.6	0.000636	0.015316	0.599609
	S15	3	101.2	-0.00012	0.01444	0.565338
	S15	7	102.6	-0.00183	0.012481	0.488647
	S15	11	100	0.001416	0.016213	0.634754
					Average	
					SLX-10-3=	0.52
Std dev =			0.09271	CoeffVar=	0.178	

Table B15 Chloride Content: Siloxane on Slabs - Week 20

		SILOXANE					
	Specimen	Location	mV	%Cl/VPI	%Cl/ADJ	lb/cu yd	
WEEK 20	S13	1	100.5	0.000764	0.015464	0.605405	
	S13	4	101.5	-0.0005	0.014011	0.548523	
	S13	8	104.1	-0.00354	0.010506	0.411324	
	DEPTH	S14	1	100.1	0.001284	0.016062	0.628835
		S14	4	103.9	-0.00332	0.010763	0.421355
		S14	8	102.3	-0.00147	0.012892	0.504703
	1	S15	1	102.1	-0.00123	0.013168	0.515521
		S15	4	103.2	-0.00253	0.011676	0.457133
		S15	8	103.4	-0.00276	0.011413	0.446803
					Average		
					SLX-20-1 =	0.5	
Std dev = 0.078157					CoeffVar =	0.156	
		SILOXANE					
	Specimen	Location	mV	%Cl/VPI	%Cl/ADJ	lb/cu yd	
WEEK 20	S13	1	103.1	-0.00241	0.011809	0.46233	
	S13	4	102.7	-0.00194	0.012346	0.483339	
	S13	8	103.3	-0.00264	0.011544	0.451957	
	DEPTH	S14	1	100.3	0.001023	0.015762	0.617071
		S14	4	104.2	-0.00365	0.010379	0.40634
		S14	8	103	-0.00229	0.011943	0.467549
	2	S15	1	103.9	-0.00332	0.010763	0.421355
		S15	4	103.3	-0.00264	0.011544	0.451957
		S15	8	103.3	-0.00264	0.011544	0.451957
					Average		
					SLX-20-2	0.47	
Std dev = 0.060456					CoeffVar =	0.129	
		SILOXANE					
	Specimen	Location	mV	%Cl/VPI	%Cl/ADJ	lb/cu yd	
WEEK 20	S13	1	104.3	-0.00107	0.013351	0.522708	
	S13	4	104.5	-0.00131	0.013071	0.511731	
	S13	8	103.9	-0.00058	0.013919	0.544942	
	DEPTH	S14	1	106.1	-0.00319	0.010911	0.427185
		S14	4	104.6	-0.00144	0.012932	0.506278
		S14	8	104.2	-0.00095	0.013492	0.528231
	3	S15	1	108	-0.00526	0.00853	0.333946
		S15	4	106.7	-0.00386	0.010139	0.396927
		S15	8	105.6	-0.00262	0.011571	0.452993
					Average		
					SLX-20-3	0.47	
Std dev = 0.071425					CoeffVar =	0.152	

Table B16 Chloride Content: Siloxane on Slabs - Week 30

		SILOXANE				
	Specimen	Location	mV	%Cl/VPI	%Cl/ADJ	lb/cu yd
WEEK 30 DEPTH 1	S13	2	98.1	0.003197	0.018263	0.715016
	S13	5	104.2	-0.00454	0.009363	0.366548
	S13	10	104	-0.00431	0.009619	0.376568
	S14	52	104.8	-0.00519	0.008608	0.337009
	S14	5	102.5	-0.00258	0.011611	0.454557
	S14	10	103.7	-0.00398	0.010007	0.391761
	S15	2	101.6	-0.00149	0.01287	0.503854
	S15	5	103.3	-0.00352	0.010532	0.41233
	S15	10	103.5	-0.00375	0.010268	0.402001
					Average	
					SLX-30-1=	0.44
Std dev = 0.114283					CoeffVar=	0.26
		SILOXANE				
	Specimen	Location	mV	%Cl/VPI	%Cl/ADJ	lb/cu yd
WEEK 30 DEPTH 2	S13	2	100.4	3.76E-05	0.014627	0.572659
	S13	5	101.7	-0.00161	0.012727	0.498281
	S13	10	102.4	-0.00246	0.011748	0.45994
	S14	2	102.4	-0.00246	0.011748	0.45994
	S14	5	103.8	-0.00409	0.009877	0.386675
	S14	10	103.6	-0.00386	0.010137	0.39687
	S15	2	101.1	-0.00086	0.013591	0.532087
	S15	5	103.4	-0.00364	0.0104	0.407154
	S15	10	101.6	-0.00149	0.01287	0.503854
					Average	
					SLX-30-2	0.47
Std dev = 0.063997					CoeffVar=	0.136
		SILOXANE				
	Specimen	Location	mV	%Cl/VPI	%Cl/ADJ	lb/cu yd
WEEK 30 DEPTH 3	S13	10	92.3	0.012719	0.029225	1.144149
	S13	2	103.3	-0.00352	0.010532	0.41233
	S13	5	105.8	-0.00625	0.007394	0.289458
	S14	2	104.7	-0.00508	0.008733	0.341879
	S14	5	103.7	-0.00398	0.010007	0.391761
	S14	10	104	-0.00431	0.009619	0.376568
	S15	2	103	-0.00317	0.010932	0.427993
	S15	5	104.4	-0.00476	0.009109	0.356616
	S15	10	101.9	-0.00186	0.012445	0.487207
					Average	
					SLX-30-3	0.39
Std dev = 0.059702					CoeffVar=	0.153

Table B17 Chloride Content: Control Wall Section - Week 11

CONTROL							
WEEK	Specimen	Location	mV	%Cl/VPI	%Cl/ADJ	lb/cu yd	
11	W1	1	75	0.059579	0.083163	3.255821	
	W1	2	87.9	0.022163	0.040094	1.569697	
	W1	3	73	0.067414	0.092181	3.608893	
	DEPTH	W1	4	65.3	0.104533	0.134906	5.281586
	1	W1	5	66.7	0.096863	0.126078	4.935963
					Average		
					CTL-11-1=	3.73	
Std dev = 1.480556					CoeffVar=	0.397	
CONTROL							
WEEK	Specimen	Location	mV	%Cl/VPI	%Cl/ADJ	lb/cu yd	
11	W1	1	95.7	0.007618	0.023352	0.914249	
	W1	2	102	-0.00111	0.013307	0.520964	
	W1	3	95.4	0.008094	0.0239	0.935694	
	DEPTH	W1	4	96.3	0.006684	0.022277	0.872159
	2	W1	5	90.8	0.016193	0.033223	1.300669
					Average		
					CTL-11-2=	0.81	
Std dev = 0.194996					CoeffVar=	0.241	
CONTROL							
WEEK	Specimen	Location	mV	%Cl/VPI	%Cl/ADJ	lb/cu yd	
11	W1	3	97.7	0.004594	0.019872	0.777973	
	W1	2	90	0.017768	0.035036	1.371646	
	W1	1	103.2	-0.00253	0.011676	0.457133	
	DEPTH	W1	4	98.9	0.002897	0.017919	0.701528
	3	W1	5	102.6	-0.00183	0.012481	0.488647
					Average		
					CTL-11-3=	0.55	
Std dev = 0.132941					CoeffVar=	0.242	

Table B18 Chloride Content: Control Wall Section - Week 21

CONTROL							
WEEK	Specimen	Location	mV	%Cl/VPI	%Cl/ADJ	lb/cu yd	
21	W1	1	67	0.110137	0.141357	5.534117	
	W1	2	58.8	0.168263	0.208262	8.153473	
	W1	3	63.5	0.132506	0.167105	6.542152	
	DEPTH	W1	4	67.5	0.107203	0.13798	5.401918
	W1	5	67.5	0.107203	0.13798	5.401918	
1						Average	
					CTL-21-1	6.21	
Std dev = 1.188505					CoeffVar=	0.191	
CONTROL							
WEEK	Specimen	Location	mV	%Cl/VPI	%Cl/ADJ	lb/cu yd	
21	W1	2	88.5	0.026431	0.045008	1.762052	
	W1	1	100.4	0.004115	0.019321	0.756414	
	W1	3	101.1	0.00312	0.018176	0.711577	
	DEPTH	W1	4	102.5	0.001217	0.015984	0.625792
	W1	5	101.3	0.002841	0.017855	0.699009	
2						Average	
					CTL-21-2	0.7	
Std dev = 0.054195					CoeffVar=	0.077	
CONTROL							
WEEK	Specimen	Location	mV	%Cl/VPI	%Cl/ADJ	lb/cu yd	
21	W1	1	106.9	-0.00408	0.009885	0.387011	
	W1	2	104.2	-0.00095	0.013492	0.528231	
	W1	3	104	-0.0007	0.013776	0.539348	
	DEPTH	W1	4	104.4	-0.00119	0.013211	0.517208
	W1	5	106.5	-0.00364	0.010394	0.406928	
3						Average	
					CTL-21-3	0.48	
Std dev = 0.072679					CoeffVar=	0.151	

Table B19 Chloride Content: Control Wall Section - Week 30

CONTROL								
WEEK	Specimen	Location	mV	%Cl/VPI	%Cl/ADJ	lb/cu yd		
30	W1	1	59.6	0.147183	0.183999	7.203544		
	W1	2	54.4	0.192171	0.235782	9.230846		
	W1	3	59	0.151869	0.189393	7.414739		
	W1	4	57	0.168405	0.208427	8.15991		
	W1	5	58.4	0.15668	0.19493	7.63152		
DEPTH						Average		
1						CTL-30-1 =	7.93	
					Std dev =	0.810457	CoeffVar =	0.102
CONTROL								
WEEK	Specimen	Location	mV	%Cl/VPI	%Cl/ADJ	lb/cu yd		
30	W1	1	88.2	0.021058	0.038823	1.519923		
	W1	2	82	0.036863	0.057015	2.232135		
	W1	3	90	0.017214	0.034398	1.346668		
	W1	4	96.5	0.005588	0.021016	0.822794		
	W1	5	87.1	0.02356	0.041703	1.632679		
DEPTH						Average		
2						CTL-30-2 =	1.51	
					Std dev =	0.508811	CoeffVar =	0.337
CONTROL								
WEEK	Specimen	Location	mV	%Cl/VPI	%Cl/ADJ	lb/cu yd		
30	W1	1	103.3	-0.00352	0.010532	0.41233		
	W1	2	104.4	-0.00476	0.009109	0.356616		
	W1	3	105.6	-0.00604	0.007632	0.298803		
	W1	4	104.7	-0.00508	0.008733	0.341879		
	W1	5	105.6	-0.00604	0.007632	0.298803		
DEPTH						Average		
3						CTL-30-3 =	0.34	
					Std dev =	0.047147	CoeffVar =	0.139

**Table B20 Chloride Content: Water-Based Epoxy on Wall -
Week 11**

WATER-BASED EPOXY						
WEEK	Specimen	Location	mV	%Cl/VPI	%Cl/ADJ	lb/cu yd
11	W2	1	65.8	0.101742	0.131694	5.155814
	W2	2	98.2	0.003877	0.019046	0.745652
	W2	3	95	0.008738	0.024641	0.964711
	W2	4	99.9	0.001547	0.016365	0.640697
	W2	5	92.9	0.012301	0.028743	1.125298
DEPTH					Average	
1					WBE-11-1	0.87
			Std dev = 0.217705		CoeffVar=	0.25
WATER-BASED EPOXY						
WEEK	Specimen	Location	mV	%Cl/VPI	%Cl/ADJ	lb/cu yd
11	W2	1	86.6	0.025084	0.043457	1.701333
	W2	2	98.1	0.004019	0.01921	0.752062
	W2	3	100.8	0.00038	0.015021	0.588089
	W2	4	101.5	-0.0005	0.014011	0.548523
	W2	5	102.2	-0.00135	0.013029	0.510101
DEPTH					Average	
2					WBE-11-2	0.6
			Std dev = 0.106452		CoeffVar=	0.177
WATER-BASED EPOXY						
WEEK	Specimen	Location	mV	%Cl/VPI	%Cl/ADJ	lb/cu yd
11	W2	3	100.5	0.000764	0.015464	0.605405
	W2	2	94.5	0.009558	0.025586	1.001673
	W2	1	101.7	-0.00074	0.013727	0.53743
	W2	4	99.8	0.00168	0.016518	0.646666
	W2	5	102.9	-0.00218	0.012076	0.47279
DEPTH					Average	
3					WBE-11-3	0.55
			Std dev = 0.087886		CoeffVar=	0.16

**Table B21 Chloride Content: Water-Based Epoxy on Wall -
Week 21**

WATER-BASED EPOXY							
WEEK	Specimen	Location	mV	%Cl/VPI	%Cl/ADJ	lb/cu yd	
21	W2	1	91.1	0.020554	0.038243	1.497218	
	W2	2	98	0.007759	0.023515	0.920627	
	W2	3	99.7	0.00514	0.020501	0.802599	
	DEPTH	W2	4	90.2	0.022516	0.040501	1.585613
	1	W2	5	94.8	0.013231	0.029814	1.167206
					Average		
					WBE-21-1	1.19	
			Std dev =	0.344218	CoeffVar=	0.289	
WATER-BASED EPOXY							
WEEK	Specimen	Location	mV	%Cl/VPI	%Cl/ADJ	lb/cu yd	
21	W2	1	104.9	-0.0018	0.012517	0.490055	
	W2	2	103.9	-0.00058	0.013919	0.544942	
	W2	3	104.4	-0.00119	0.013211	0.517208	
	DEPTH	W2	4	105	-0.00191	0.01238	0.484693
	2	W2	5	104.3	-0.00107	0.013351	0.522708
					Average		
					WBE-21-2	0.51	
			Std dev =	0.02477	CoeffVar=	0.049	
WATER-BASED EPOXY							
WEEK	Specimen	Location	mV	%Cl/VPI	%Cl/ADJ	lb/cu yd	
21	W2	1	105.9	-0.00296	0.011174	0.437443	
	W2	2	104.7	-0.00156	0.012793	0.500847	
	W2	3	104	-0.0007	0.013776	0.539348	
	DEPTH	W2	4	105.2	-0.00215	0.012108	0.474037
	3	W2	5	105.6	-0.00262	0.011571	0.452993
					Average		
					WBE-21-3	0.48	
			Std dev =	0.040399	CoeffVar=	0.084	

Table B22 Chloride Content: Water-Based Epoxy on Wall -
Week 30

WATER-BASED EPOXY							
WEEK	Specimen	Location	mV	%Cl/VPI	%Cl/ADJ	lb/cu yd	
30	W2	1	62.6	0.125501	0.159041	6.226467	
	W2	2	78.7	0.047184	0.068895	2.697253	
	W2	3	78.3	0.048539	0.070455	2.758305	
	DEPTH	W2	4	84.2	0.030761	0.049991	1.957162
	1	W2	5	92.6	0.012166	0.028587	1.119197
					Average		
					WBE-30-1	2.13	
			Std dev = 0.767703	CoeffVar=		0.36	
WATER-BASED EPOXY							
WEEK	Specimen	Location	mV	%Cl/VPI	%Cl/ADJ	lb/cu yd	
30	W2	1	86.9	0.024028	0.042242	1.653766	
	W2	2	104.9	-0.0053	0.008484	0.33216	
	W2	3	105.2	-0.00562	0.008116	0.31774	
	DEPTH	W2	4	101.9	-0.00186	0.012445	0.487207
	2	W2	5	106.5	-0.00696	0.006574	0.257383
					Average		
					WBE-30-2	0.35	
			Std dev = 0.097903	CoeffVar=		0.28	
WATER-BASED EPOXY							
WEEK	Specimen	Location	mV	%Cl/VPI	%Cl/ADJ	lb/cu yd	
30	W2	1	106.7	-0.00716	0.006345	0.248396	
	W2	2	103	-0.00317	0.010932	0.427993	
	W2	3	106.6	-0.00706	0.006459	0.25288	
	DEPTH	W2	4	107.2	-0.00765	0.00578	0.22627
	3	W2	5	107.4	-0.00784	0.005557	0.217553
					Average		
					WBE-30-3	0.27	
			Std dev = 0.087003	CoeffVar=		0.322	

**Table B23 Chloride Content: Solvent-Based Epoxy on Wall -
Week 11**

SOLVENT-BASED EPOXY							
WEEK	Specimen	Location	mV	%Cl/VPI	%Cl/ADJ	lb/cu yd	
11	W3	1	82.5	0.035413	0.055346	2.166784	
	W3	2	101.5	-0.0005	0.014011	0.548523	
	W3	3	99.4	0.002215	0.017134	0.670794	
	W3	4	90	0.017768	0.035036	1.371646	
	W3	5	93.6	0.011078	0.027336	1.07019	
DEPTH						Average	
1						SBE-11-1	0.92
			Std dev = 0.377073			CoeffVar=	0.41
SOLVENT-BASED EPOXY							
WEEK	Specimen	Location	mV	%Cl/VPI	%Cl/ADJ	lb/cu yd	
11	W3	1	100.4	0.000893	0.015612	0.611226	
	W3	2	103.2	-0.00253	0.011676	0.457133	
	W3	3	102.5	-0.00171	0.012618	0.493976	
	W3	4	101.5	-0.0005	0.014011	0.548523	
	W3	5	101.3	-0.00025	0.014297	0.559709	
DEPTH						Average	
2						SBE-11-2	0.53
			Std dev = 0.059888			CoeffVar=	0.113
SOLVENT-BASED EPOXY							
WEEK	Specimen	Location	mV	%Cl/VPI	%Cl/ADJ	lb/cu yd	
11	W3	2	93.6	0.011078	0.027336	1.07019	
	W3	1	103.3	-0.00264	0.011544	0.451957	
	W3	3	100.8	0.00038	0.015021	0.588089	
	W3	4	101.1	5.82E-07	0.014585	0.57099	
	W3	5	102.8	-0.00206	0.012211	0.478054	
DEPTH						Average	
3						SBE-11-3	0.52
			Std dev = 0.067342			CoeffVar=	0.13

**Table B24 Chloride Content: Solvent-Based Epoxy on Wall -
Week 21**

SOLVENT-BASED EPOXY						
WEEK	Specimen	Location	mV	%Cl/VPI	%Cl/ADJ	lb/cu yd
21	W3	1	93.7	0.01529	0.032183	1.259979
	W3	2	88.2	0.027152	0.045837	1.794528
	W3	3	86.8	0.030639	0.049851	1.951653
	W3	4	88.2	0.027152	0.045837	1.794528
	W3	5	96.3	0.010574	0.026755	1.04746
DEPTH						
1						
					Average	
					SBE-21-1	1.57
			Std dev = 0.392315		CoeffVar=	0.25
SOLVENT-BASED EPOXY						
WEEK	Specimen	Location	mV	%Cl/VPI	%Cl/ADJ	lb/cu yd
21	W3	1	104.8	-0.00168	0.012655	0.49544
	W3	2	102.9	0.000693	0.015382	0.602201
	W3	3	101.2	0.002981	0.018015	0.70528
	W3	4	103.1	0.000435	0.015084	0.590554
	W3	5	102.3	0.001482	0.01629	0.637738
DEPTH						
2						
					Average	
					SBE-21-2	0.61
			Std dev = 0.076387		CoeffVar=	0.125
SOLVENT-BASED EPOXY						
WEEK	Specimen	Location	mV	%Cl/VPI	%Cl/ADJ	lb/cu yd
21	W3	1	105.4	-0.00239	0.011838	0.463471
	W3	2	103	0.000564	0.015233	0.596365
	W3	3	106.5	-0.00364	0.010394	0.406928
	W3	4	106.9	-0.00408	0.009885	0.387011
	W3	5	104.8	-0.00168	0.012655	0.49544
DEPTH						
3						
					Average	
					SBE-21-3	0.47
			Std dev = 0.082951		CoeffVar=	0.176

**Table B25 Chloride Content: Solvent-Based Epoxy on Wall -
Week 30**

SOLVENT-BASED EPOXY							
WEEK	Specimen	Location	mV	%Cl/VPI	%Cl/ADJ	lb/cu yd	
30	W3	1	85.3	0.027922	0.046724	1.829239	
	W3	2	75.8	0.057563	0.080841	3.164936	
	W3	3	65.9	0.104702	0.135102	5.289226	
	W3	4	83.2	0.033462	0.053101	2.078892	
	W3	5	80	0.04294	0.064011	2.506013	
DEPTH						Average	
1						SBE-30-1	2.97
			Std dev =	1.389913	CoeffVar=	0.468	
SOLVENT-BASED EPOXY							
WEEK	Specimen	Location	mV	%Cl/VPI	%Cl/ADJ	lb/cu yd	
30	W3	1	104.6	-0.00498	0.008857	0.34677	
	W3	2	103.7	-0.00398	0.010007	0.391761	
	W3	3	91.4	0.014425	0.031188	1.220991	
	W3	4	103.8	-0.00409	0.009877	0.386675	
	W3	5	99.9	0.000698	0.015387	0.602406	
DEPTH						Average	
2						SBE-30-2	0.59
			Std dev =	0.366778	CoeffVar=	0.622	
SOLVENT-BASED EPOXY							
WEEK	Specimen	Location	mV	%Cl/VPI	%Cl/ADJ	lb/cu yd	
30	W3	1	105.9	-0.00635	0.007275	0.284816	
	W3	2	106.2	-0.00666	0.006922	0.27101	
	W3	3	103.5	-0.00375	0.010268	0.402001	
	W3	4	106.1	-0.00655	0.007039	0.275592	
	W3	5	106	-0.00645	0.007157	0.280194	
DEPTH						Average	
3						SBE-30-3	0.3
			Std dev =	0.055736	CoeffVar=	0.186	

Table B26 Chloride Content: Silane on Wall - Week 11

SILANE							
WEEK	Specimen	Location	mV	%Cl/VPI	%Cl/ADJ	lb/cu yd	
11	W4	1	102.6	-0.00183	0.012481	0.488647	
	W4	2	103.9	-0.00332	0.010763	0.421355	
	W4	3	99.2	0.002486	0.017446	0.68301	
	DEPTH	W4	4	100.2	0.001153	0.015912	0.62294
	1	W4	5	98.1	0.004019	0.01921	0.752062
					Average		
					SIL-11-1=	0.59	
Std dev =			0.13661	CoeffVar=	0.232		
SILANE							
WEEK	Specimen	Location	mV	%Cl/VPI	%Cl/ADJ	lb/cu yd	
11	W4	1	103.4	-0.00276	0.011413	0.446803	
	W4	2	103.3	-0.00264	0.011544	0.451957	
	W4	3	102.2	-0.00135	0.013029	0.510101	
	DEPTH	W4	4	99.6	0.001946	0.016825	0.658679
	2	W4	5	102.3	-0.00147	0.012892	0.504703
					Average		
					SIL-11-2=	0.51	
Std dev =			0.085729	CoeffVar=	0.168		
SILANE							
WEEK	Specimen	Location	mV	%Cl/VPI	%Cl/ADJ	lb/cu yd	
11	W4	2	98.9	0.002897	0.017919	0.701528	
	W4	1	103.2	-0.00253	0.011676	0.457133	
	W4	3	101.2	-0.00012	0.01444	0.565338	
	DEPTH	W4	4	102.4	-0.00159	0.012754	0.499329
	3	W4	5	103.7	-0.0031	0.011021	0.43147
					Average		
					SIL-11-3=	0.49	
Std dev =			0.058474	CoeffVar=	0.119		

Table B27 Chloride Content: Silane on Wall - Week 21

SILANE						
WEEK	Specimen	Location	mV	%Cl/VPI	%Cl/ADJ	lb/cu yd
21	W4	1	103	0.000564	0.015233	0.596365
	W4	2	102.7	0.000954	0.015682	0.613946
	W4	3	96.6	0.010062	0.026166	1.024409
	W4	4	103.1	0.000435	0.015084	0.590554
	W4	5	102.9	0.000693	0.015382	0.602201
DEPTH						Average
1						SIL-21-1= 0.69
			Std dev = 0.189656			CoeffVar= 0.275
SILANE						
WEEK	Specimen	Location	mV	%Cl/VPI	%Cl/ADJ	lb/cu yd
21	W4	1	104.3	-0.00107	0.013351	0.522708
	W4	2	105.3	-0.00227	0.011973	0.468743
	W4	3	103.3	0.000178	0.014789	0.579006
	W4	4	105.3	-0.00227	0.011973	0.468743
	W4	5	105.9	-0.00296	0.011174	0.437443
DEPTH						Average
2						SIL-21-2= 0.5
			Std dev = 0.055937			CoeffVar= 0.112
SILANE						
WEEK	Specimen	Location	mV	%Cl/VPI	%Cl/ADJ	lb/cu yd
21	W4	1	103.2	0.000306	0.014937	0.584768
	W4	2	105.4	-0.00239	0.011838	0.463471
	W4	3	106.1	-0.00319	0.010911	0.427185
	W4	4	105.5	-0.0025	0.011704	0.458221
	W4	5	105.1	-0.00203	0.012244	0.479354
DEPTH						Average
3						SIL-21-3= 0.48
			Std dev = 0.060166			CoeffVar= 0.125

Table B28 Chloride Content: Silane on Wall - Week 30

SILANE						
WEEK	Specimen	Location	mV	%Cl/VPI	%Cl/ADJ	lb/cu yd
30	W4	1	102.2	-0.00222	0.012025	0.470775
	W4	2	101	-0.00074	0.013737	0.537808
	W4	3	103.3	-0.00352	0.010532	0.41233
	W4	4	101.9	-0.00186	0.012445	0.487207
	W4	5	95.1	0.007822	0.023588	0.923456
DEPTH						Average
1						SIL-30-1 = 0.57
			Std dev = 0.204609			CoeffVar = 0.359
SILANE						
WEEK	Specimen	Location	mV	%Cl/VPI	%Cl/ADJ	lb/cu yd
30	W4	1	102.8	-0.00294	0.011202	0.438549
	W4	2	106.3	-0.00676	0.006806	0.266448
	W4	3	105.6	-0.00604	0.007632	0.298803
	W4	4	106.3	-0.00676	0.006806	0.266448
	W4	5	105.5	-0.00594	0.007752	0.303507
DEPTH						Average
2						SIL-30-2 = 0.31
			Std dev = 0.071367			CoeffVar = 0.23
SILANE						
WEEK	Specimen	Location	mV	%Cl/VPI	%Cl/ADJ	lb/cu yd
30	W4	1	106.2	-0.00666	0.006922	0.27101
	W4	2	106.8	-0.00726	0.006231	0.243932
	W4	3	107.5	-0.00794	0.005446	0.213223
	W4	4	106.6	-0.00706	0.006459	0.25288
	W4	5	105	-0.00541	0.008361	0.327332
DEPTH						Average
3						SIL-30-3 = 0.26
			Std dev = 0.042243			CoeffVar = 0.162

Table B29 Chloride Content: Siloxane on Wall - Week 11

SILOXANE							
WEEK	Specimen	Location	mV	%Cl/VPI	%Cl/ADJ	lb/cu yd	
11	W5	1	106.4	-0.00597	0.007709	0.301818	
	W5	2	102.8	-0.00206	0.012211	0.478054	
	W5	3	102.8	-0.00206	0.012211	0.478054	
	DEPTH	W5	4	98.5	0.003453	0.018559	0.726583
	1	W5	5	100.3	0.001023	0.015762	0.617071
					Average		
					SLX-11-1=	0.52	
Std dev =			0.16064	CoeffVar=		0.309	
SILOXANE							
WEEK	Specimen	Location	mV	%Cl/VPI	%Cl/ADJ	lb/cu yd	
11	W5	1	102.9	-0.00218	0.012076	0.47279	
	W5	2	99.3	0.002351	0.01729	0.676889	
	W5	3	102.2	-0.00135	0.013029	0.510101	
	DEPTH	W5	4	100.4	0.000893	0.015612	0.611226
	2	W5	5	101.2	-0.00012	0.01444	0.565338
					Average		
					SLX-11-2=	0.57	
Std dev =			0.08085	CoeffVar=		0.142	
SILOXANE							
WEEK	Specimen	Location	mV	%Cl/VPI	%Cl/ADJ	lb/cu yd	
11	W5	3	93.3	0.011598	0.027934	1.09361	
	W5	2	97.5	0.004885	0.020207	0.791092	
	DEPTH	W5	1	101.2	-0.00012	0.01444	0.565338
	3	W5	4	102.6	-0.00183	0.012481	0.488647
		W5	5	103.5	-0.00287	0.011281	0.44167
					Average		
					SLX-11-3=	0.5	
Std dev =			0.062426	CoeffVar=		0.125	

Table B30 Chloride Content: Siloxane on Wall - Week 21

SILOXANE							
WEEK	Specimen	Location	mV	%Cl/VPI	%Cl/ADJ	lb/cu yd	
21	W5	1	103.2	0.000306	0.014937	0.584768	
	W5	2	103.1	0.000435	0.015084	0.590554	
	W5	3	101.9	0.002019	0.016908	0.661935	
	DEPTH	W5	4	95.4	0.012148	0.028567	1.118393
	1	W5	5	102.4	0.001349	0.016137	0.631752
Average							
SLX-21-1=						0.72	
Std dev = 0.226323						CoeffVar=	0.314
SILOXANE							
WEEK	Specimen	Location	mV	%Cl/VPI	%Cl/ADJ	lb/cu yd	
21	W5	1	105.2	-0.00215	0.012108	0.474037	
	W5	2	106.1	-0.00319	0.010911	0.427185	
	W5	3	106.2	-0.0033	0.010781	0.422089	
	DEPTH	W5	4	104.9	-0.0018	0.012517	0.490055
	2	W5	5	104.2	-0.00095	0.013492	0.528231
Average							
SLX-21-2=						0.47	
Std dev = 0.044508						CoeffVar=	0.095
SILOXANE							
WEEK	Specimen	Location	mV	%Cl/VPI	%Cl/ADJ	lb/cu yd	
21	W5	1	107.1	-0.0043	0.009634	0.377178	
	W5	2	105.5	-0.0025	0.011704	0.458221	
	W5	3	106.5	-0.00364	0.010394	0.406928	
	DEPTH	W5	4	104.7	-0.00156	0.012793	0.500847
	3	W5	5	99.5	0.005439	0.020844	0.816048
Average							
SLX-21-3=						0.51	
Std dev = 0.176549						CoeffVar=	0.346

Table B31 Chloride Content: Siloxane on Wall - Week 30

SILOXANE							
WEEK	Specimen	Location	mV	%Cl/VPI	%Cl/ADJ	lb/cu yd	
30	W5	1	97.2	0.004521	0.019788	0.774716	
	W5	2	101.8	-0.00174	0.012586	0.492732	
	W5	3	103.9	-0.0042	0.009747	0.38161	
	W5	4	97.7	0.003779	0.018934	0.741261	
	W5	5	83.5	0.03264	0.052154	2.041815	
DEPTH						Average	
1	Std dev = 0.666766					SLX-30-1 =	0.89
					CoeffVar =	0.749	
SILOXANE							
WEEK	Specimen	Location	mV	%Cl/VPI	%Cl/ADJ	lb/cu yd	
30	W5	1	106.4	-0.00686	0.00669	0.261905	
	W5	2	106.8	-0.00726	0.006231	0.243932	
	W5	3	103.1	-0.00329	0.010798	0.422749	
	W5	4	105.5	-0.00594	0.007752	0.303507	
	W5	5	104.8	-0.00519	0.008608	0.337009	
DEPTH						Average	
2	Std dev = 0.070868					SLX-30-2	0.31
					CoeffVar =	0.229	
SILOXANE							
WEEK	Specimen	Location	mV	%Cl/VPI	%Cl/ADJ	lb/cu yd	
30	W5	1	106.3	-0.00676	0.006806	0.266448	
	W5	2	102.2	-0.00222	0.012025	0.470775	
	W5	3	105.7	-0.00614	0.007513	0.294121	
	W5	4	106.7	-0.00716	0.006345	0.248396	
	W5	5	105.5	-0.00594	0.007752	0.303507	
DEPTH						Average	
3	Std dev = 0.088901					SLX-30-3	0.32
					CoeffVar =	0.278	

Appendix C

Photographs Depicting Surface Wear of Epoxies

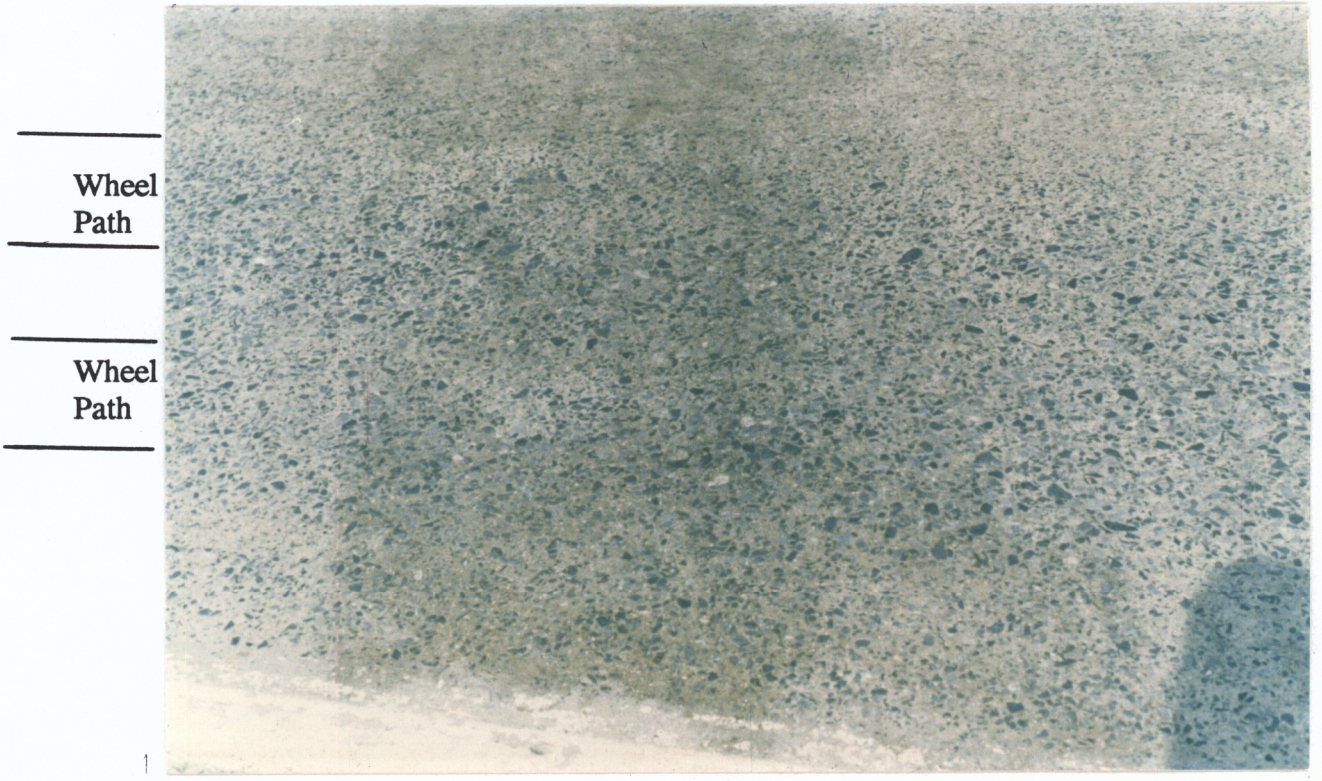


Figure C1 Solvent-Based Epoxy Wear in Wheel Path: I-81 Bridge

	erage	COV	Average	COV	Average	COV
Wheel Path	1.33	0.38	1.1	0.4	1.63	0.2
	1.03	0.34	0.83	0.07	1.3	0.47
	0.89		0.73		1.09	
	0.79		0.64		1	
Pepper's Ferry Bridge over New River						
	WBE verage	COV	SBE Average	COV	SIL Average	COV
	1.47	0.22	1.17	0.41	1.47	0.55
	1.3	0.31	1.13	0.36	1.1	---
	1.43		1.14		1.43	
	0.93		0.81		0.79	

Figure C2 Solvent-Based Epoxy Wear in Wheel Path: Pepper's Ferry Bridge

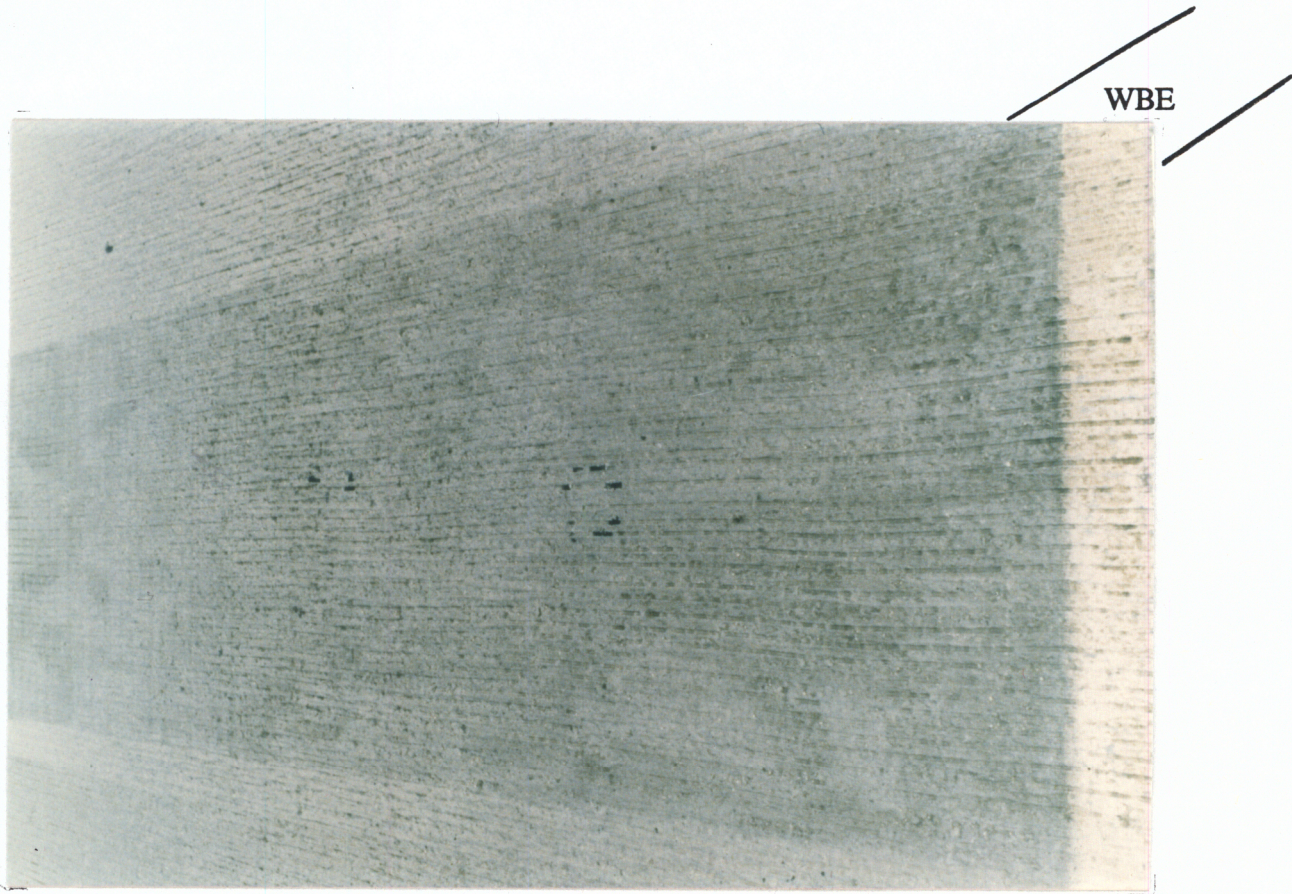


Figure C2 Water-Based Epoxy Wear in Wheel Path: I-81 Bridge

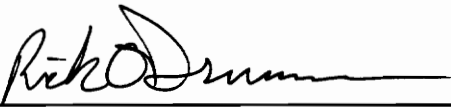
Wheel
Path



Figure C2 Water-Based Epoxy Wear in Wheel Path: Pepper's Ferry Bridge

VITA

The author was born January 21, 1963, in Huntington, New York. He graduated from Freeport Area Senior High School in Freeport, Pennsylvania, in June, 1980. That fall he enrolled in Franklin and Marshall College in Lancaster, Pennsylvania and in May, 1984, graduated with a Bachelor's degree majoring in Geology. After one year of managing fast-food chicken restaurants in New Orleans, Louisiana, he then began to teach at the high school level at Brother Martin High School in New Orleans. At the same time, he attended Tulane University and the University of New Orleans for coursework toward teacher certification, which he received in the summer of 1989. In the fall of 1989, he began the pursuit of a Bachelor's degree in Civil Engineering at Louisiana State University. He received that degree in May, 1991. The fall of that year he began his studies at Virginia Polytechnic Institute and State University, concentrating in the areas of structures and materials and working as a graduate research assistant.



Rick O. Drumm