MDOT RC-1424
CSD-2002-03

MDOT

Criteria & Benefits of Penetrating Sealants for Concrete Bridge Decks

Upul Attanayaka
Dr. Haluk Aktan
Dr. Simon Ng

Center for Structural Durability
A Michigan DOT Center of Excellence

Wayne State University

December 2002

TESTING AND RESEARCH SECTION
CONSTRUCTION AND TECHNOLOGY DIVISION
RESEARCH REPORT NO. RC-1424

Research

New Abstract Form I:/forms/newblankabstractsheet (3/2002)

Technical Report Documentation Page

1. Report No. Research Report RC-1424	2. Government Accession No.	3. MDOT Project Manager John F. Staton, P.E.
4. Title and Subtitle Criteria and Benefits of Penetrating Sealants for Concrete Bridge Decks		5. Report Date
7. Author(s) Upul Attanayaka, Dr. Simon Ng, Ph.D, P.E., Dr. Haluk Aktan, Ph.D, P.E		6. Performing Organization Code
9. Performing Organization Name and Address Department of Civil & Environmental Engineering College of Engineering Wayne State University 5050 Anthony Wayne Drive Detroit, MI 48202		8. Performing Org Report No.
12. Sponsoring Agency Name and Address Michigan Department of Transportation Construction and Technology Division P.O. Box 30049 Lansing, MI 48909		10. Work Unit No. (TRAIS)
		11. Contract Number: 01-0339
		11(a). Authorization Number:
15. Supplementary Notes		13. Type of Report & Period Covered
		14. Sponsoring Agency Code

16. Abstract

The study presented in this report evaluates the potential durability gained by the use of penetrating sealants on concrete bridge decks. The primary conclusion of this report is penetrating sealants are an effective means of protecting concrete bridge decks. The factors affecting the depth of penetration are identified through a fundamental approach and the literature on penetrating sealants, concrete deterioration, concrete durability, and concrete permeability. Properties and the use of silane, siloxane, and high molecular weight methacrylate sealers are discussed. The use of high molecular weight methacrylate is recommended based on its extensive applications in the field. Silane and siloxane penetrating sealers can be used on new decks. High molecular weight methacrylate (HMWM) in conjunction with silane sealers can be used on cracked decks. If the maximum crack width is less than 0.002-inches, silane sealers are adequate to seal the deck. When the crack width is between 0.002- and 0.08-inches, silane and HMWM sealers can be applied provided adequate drying period is maintained between silane and HMWM applications. A field test method for evaluating the effectiveness of penetrating sealants is outlined. Electrical resistivity measurement technique is proposed as a means of obtaining field data. Cores are taken from the samples cast, cured, treated, and subjected to the same environmental conditions as the concrete bridge deck. These cores can be used for recording visible and effective depth of penetrations using splitting test and the abrasion test method recommended by Alberta Transportation and Utilities, respectively.

17. Key Words Concrete bridge deck, Durability, Electrical resistivity, Methacrylate, Hydrophobic, Penetrating sealants, Permeability, Silane, Siloxane, Water repellents		18. Distribution Statement No restrictions. This document is available to the public through the Michigan Department of Transportation.	
19. Security Classification (report) Unclassified	20. Security Classification (Page) Unclassified	21. No of Pages	22. Price

CRITERIA AND BENEFITS OF PENETRATING SEALANTS FOR CONCRETE BRIDGE DECKS

Upul Attanayaka
Graduate Research Assistant

Dr. Haluk Aktan, P.E
Professor

Dr. Simon Ng, P.E
Professor

Submitted to:

MDOT

Submitted by:

CENTER FOR STRUCTURAL DURABILITY

A Michigan DOT Center of Excellence

WAYNE STATE UNIVERSITY

Detroit, MI 48202

DECEMBER 2002

EXECUTIVE SUMMARY

The study presented in this report evaluates the potential durability gained by the use of penetrating sealants on concrete bridge decks. The primary conclusion of this report is that penetrating sealants are an effective means of protecting concrete bridge decks. Penetrating sealants have an effective service life of four to five years. Silane and siloxane penetrating sealers can be used on new decks. High-molecular-weight methacrylate (HMWM) in conjunction with silane sealers can be used on cracked decks. If the maximum crack width is less than 0.002-inches, silane sealers are adequate to seal the deck. When the crack width is between 0.002- and 0.08-inches, silane and HMWM sealers can be applied, provided an adequate drying period is maintained between silane and HMWM applications.

Depth of penetration is one of the most important factors for the effectiveness of the penetrating sealants. In uncracked concrete, capillary suction is the governing force for sealant penetration. Based on the following equation, the properties of sealants and concrete that control the depth of penetration were identified.

$$h^2 = \frac{4k}{\eta}\frac{1}{p}\frac{\gamma . Cos\theta}{a} t$$

where

a = Mean pore radius (in)

h = Depth of penetration (in)

k = Intrinsic permeability (in^2)

p = Porosity

t = Time (s)

η = Viscosity ($lbf\text{-}s/in^2$)

θ = Contact angle (deg)

γ = Surface tension (lbf/in)

Properties of sealants and concrete that control the depth of penetration are given in the following table. The permeability coefficient (k) incorporates the effects of tortuosity, pore-surface topology, and reactivity of sealants with concrete substrate.

Sealant & Concrete Properties for Determining Optimal Penetration Depth

Concrete	Penetrating Sealants
Pore size	Viscosity
Pore distribution	Contact angle
Moisture	Surface tension
Age	Molecular size
Admixtures	Molecular weight
Crack width and density	

In addition to the properties of sealants and concrete, surface preparation, application procedures, and the prevailing weather conditions are also controlling parameters for the depth of penetration and performance.

NCHRP Report 244 (Series – II) test procedures were recognized as the sealer-selection criteria. The test procedure recommended by Alberta Transportation and Utilities (AT&U) was identified as a widely used method for finding the effective depth of sealant penetration, but the AT&U test procedure requires coring of field concrete. If coring is permissible, the splitting test also provides a visual verification of the depth of penetration. Additional testing on cores also includes neutron radiography that provides an accurate assessment of sealant performance.

In-situ nondestructive means of measuring sealant performance is done by electrical resistivity. This method utilizes surface resistivity for measuring the functioning of sealers as hydrophobic (water repellent) agents. The electrical-resistivity method can be implemented in the laboratory as well as in the field. The electrical-resistivity test for field use requires a reference measure. The field procedure needs further developments.

Based on available literature, the authors recommend a nondestructive testing procedure that can be implemented in the field for sealant evaluation. The procedure requires preparation of two 24"x 24"x 4" field specimens. Sealer will be applied on a specimen as well as the bridge deck. The other specimen is used for reference measurements. The treated specimen will be used for obtaining resistivity baseline measurements. The specimen will also be cored and analyzed for the depth of penetration, as described in the AT&U test procedure and the splitting test.

ACKNOWLEDGMENTS

The project described in this report was sponsored by the Michigan Department of Transportation through the Center for Structural Durability at Wayne State University. We appreciate the kind support of Sika Corporation, Lone Star Epoxies, Endur-O-Seal, and Fox Industries, who provided penetrating sealants for experimental studies carried out during this research. Graduate research assistants Okan Duyar of the Civil Engineering Department and Liang Xuemei and Vipul Kishore of the Chemical Engineering Department participated in this study.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1 INTRODUCTION

The length of time during which concrete structures' serviceability and safety remain is generally referred to as durability (Koichi et al., 1999). Better performance of material quality, concrete placement and curing, structural detailing and dimensioning, and maintenance increase the lifetime of concrete structures by achieving durable concrete. Deterioration processes may be due to weathering, extreme temperatures, abrasion, electrolytic action, fatigue loads, and possible attack by natural or industrial chemicals and gases which are transported by moisture. Internal deterioration of concrete may result from the alkali-aggregate reaction, volume change occurring due to the difference of thermal properties of cement paste and aggregate, and, the most important of all, the permeability of concrete. The basic constituents of concrete i.e., aggregate and cement paste—are relatively porous. In addition, voids are formed in concrete as a result of inadequate consolidation and/or bleeding. The pores, micro-cracks, and voids of the concrete allow transport of liquids and gases. As for the basic transport mechanisms, transport of vapors and inert gases takes place by diffusion and by filtration under a pressure gradient. Transport of liquid occurs by diffusion, capillary absorption, and filtration (Koichi et al., 1999).

Applications of de-icing salt introduce the chloride ions that reach the reinforcing bars through water-filled pores and/or cracks, gaps, and joints. Chloride ions cause rapid and severe corrosion that increases volume of steel bars. This increased volume exerts pressure inside the concrete, initiating tensile stresses that result in cracking and spalling of the concrete cover. Therefore, chloride ions accelerate the deterioration process.

The goal of this study is to evaluate the potential durability gained by the use of penetrating sealants on concrete bridge decks. One can take as a given that the concrete mix specified for bridge decks (MDOT Grade D, w/c of 0.45) will produce a concrete with properties that is sufficiently durable for the loads and environmental conditions in Michigan. Therefore, the gain observed from the use of additional protection with penetrating sealants or similar products will be marginal. However, our experience and the literature indicate that field practices and other construction constraints often result in a variability of concrete durability properties between decks as well as within a deck surface. For example, during concrete placement on bridge decks, the curing process generally is not initiated until the finished deck surface has sufficiently hardened. Consequently, portions of concrete that were placed first will have increased evaporation and thus will exhibit more shrinkage cracks. Additionally, the consolidation process may result in a variability of the w/c within the deck surface. Previous research conducted by Yaman et al., (2002) shows the variation of permeability on three newly constructed concrete bridge decks in Michigan (Table 1). Based on this premise, we can assert that there are vulnerable portions on the deck surface where distress will first initiate. The use of penetrating sealants provides additional protection for the portions of the deck with increased permeability due to shrinkage cracking or increased w/c. Application of penetrating sealants provides a concrete surface with more uniform durability.

Table 1. Permeability Properties of Concrete Bridge Decks after 56 Days

Bridge ID Number	Gas Permeability (10^{-13} in^2)	Gas Permeability (10^{-7} in/s)	Water Permeability (10^{-8} in/s)
S04-82062	16.00	27.00	40.00
S17-82112	26.40	44.00	66.00
S26-82251	2.64	4.40	6.60

2 PROJECT OBJECTIVE

The project objective is to establish the need and effectiveness of a two-tier bridge-deck-protection strategy. The first tier of protection is to apply protective coating, such as sealants and impregnants, to new decks. The second tier is to protect early-age-cracked decks with sealants or impregnants if there is no change to decks' wearing-surface rating. A third-tier of protection in conjunction with corrective upgrade action for aged decks with compromised deck is not discussed here.

For the first and second-tier of protection, the main objective is focused on establishing a strategy for concrete-bridge-deck protection using penetrating polymeric sealants. Two types of concrete decks are considered in this study: (1) new decks and (2) decks cracked at an early age. Cracked concrete bridge decks are again categorized as early-age-cracked concrete due to creep, shrinkage, and thermal effects.

The aim is to reduce the permeability of concrete bridge decks to a noticeable degree by using polymeric sealants that penetrate a minimum of 0.25-inches (6-mm) into the deck.

Achievement of the project objective and finalization of the study requires that several tasks be undertaken.

The first task consists of the following steps:

1. Document the fundamentals of "permeability of concrete" and the parameters affecting permeability, such as porosity, pore diameter, crack width, viscosity, surface tension, contact angle, and the application pressure.

2. Conduct a state-of-art literature review

    a. Collect the comprehensive information on the use, developments, and field performance of penetrating polymeric sealants.

    b. Document the experiences of State Highway Agencies and other countries with climates similar to Michigan.

    c. Collect information on the concrete properties and characteristics.

3. Document the theoretical fundamentals and concepts of penetration of polymeric sealants.
4. Document the properties of penetrating polymeric sealants such as viscosity, molecular size, contact angle, solubility, etc., in accordance with the concrete properties.
5. Identify types of penetrating polymeric sealants available on the market and their characteristics (properties).
6. Provide recommendations for use of sealants on concrete bridge decks.

2.1 DEFINITIONS

To protect concrete and reduce deterioration caused by moisture ingress, which transports chloride ions and other substances into concrete, several types of surface sealers are used. At the present time, we are most concerned with *penetrating* sealants. Penetrating sealants are categorized as water repellents and pore blockers. Definitions of common terms used in this report are given below.

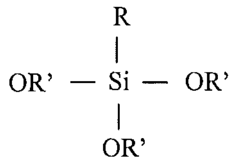
Penetrating Sealant: A liquid applied to the surface of the Portland cement concrete using gravity or spray application. The liquid may cure to form a continuous film on the pore walls or may seal the pores by blocking the voids of concrete without leaving any coating on the exterior surface of the concrete.

Water repellents: Penetrating sealers that penetrate concrete pores to some degree and coat pore walls, rendering them hydrophobic.

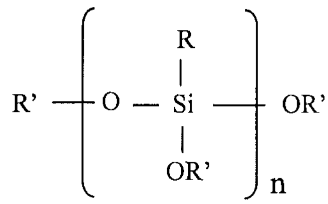
Pore blockers: Penetrating sealers that penetrate into concrete pores and plug them by blocking the pores.

Silanes: Silicon compounds of small molecules with one silicon atom.

Siloxanes: Silicon compounds with chained molecular structures with more than one silicon atom.



Molecular structure of silane

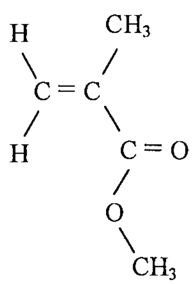


Molecular structure of siloxane

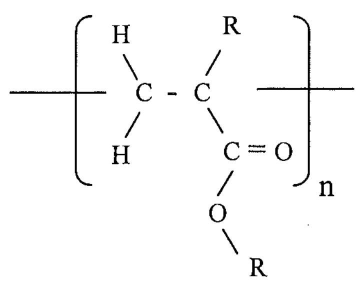
R group: Organofunctional (or alkyl) group that is responsible for the water repellency properties of silane/siloxane sealers.

OR' group: Silicon functional (or alkoxy) group that is responsible for the reactivity of silane/siloxane sealers with concrete substrate.

High–molecular-weight methacrylate (HMWM): HMWM is a broad category used to describe blends of methacrylate with various constituents.



Molecular structure of methyl methacrylate



Molecular structure of HMWM

Contact angle: The angle included between the tangent planes to the liquid-vapor interface and the solid-liquid interface. This angle is measured through the liquid phase at any point along the planes' line of contact.

Surface Tension: The energy required to expand the surface area of a liquid by a unit amount.

3 LITERATURE REVIEW

An initial review of the literature, especially the National Cooperative Highway Research Program (NCHRP) report (Cady, 1994), indicated that penetration of sealants into concrete in excess of 0.25-inches could only be achieved by using water repellents. For this reason, we focused mainly on water repellent sealants. Therefore, this literature review deals with research into widely used water repellent sealants and their chemical properties, test procedures for selecting and evaluating sealer performance, surface preparation methods, application procedures, and the influential environmental factors for the sealer performance. These topics are discussed in subsequent chapters.

NCHRP conducted extensive research on protection of reinforced concrete bridge elements and other concrete structural elements from the chlorides found in marine environments and deicing chemicals. Several sealers intended for the use on concrete surfaces have been evaluated using laboratory tests. NCHRP Report 244 (Pfeifer et al., 1981) includes recommendations for types of sealers, testing procedures for selecting sealers, and general recommendations for sealer applications. Their recommendations and test procedures (Appendix A) were for bridge surfaces, excepting those portions of the deck subject to tire abrasion.

In the NCHRP study, four laboratory-testing phases were conducted using candidate sealers selected through a survey (responses were obtained from 41 State Highway Agencies and 69 chemical or paint companies). From a list of 21 candidate sealers, five sealers have been selected through test Series-I that was designed to evaluate the water absorption and chloride intrusion characteristics of sealed concrete specimens soaked in a 15-percent NaCl solution (saltwater). The five sealers were Epoxy, methyl methacrylate, moisture-cured urethane, alkyl-alkoxy silane, and polyisobutyl methacrylate. (Note: the NCHRP Report 244 does not recommend applying alkyl-alkoxy silane on concrete surfaces that are pretreated with linseed oil.) The group of five sealers was subjected to further tests (Series-II) to study the effects of different moisture conditions on the effectiveness of sealants. Concrete specimens were cured for 21 days inside plastic bags (instead of the six days of water soaking implemented in the test Series-I) and later air-dried for 1, 5, and 20 days. The sealants were applied to the specimens at these three different ages to simulate different moisture conditions of concrete. The samples were later tested for water absorption and chloride intrusion. The objectives of test Series-III were to determine the influences of various application rates of sealers on saltwater absorption, water vapor transmission, and chloride-ion-intrusion characteristics. The test Series-IV was designed to simulate the environmental conditions in Southern and Northern climates. Based on the results of all four test Series (I, II, III, and IV), three specific materials were selected and are shown in Table 2 and Table 3.

Table 2. Reduction of Chloride Content in Concrete after Sealant Application, %

Material	Series-I	Series-II	Series-III	Series-IV	
				Northern	Southern
Epoxy	97	94	92	97	93
Methyl - methacrylate	80	91	92	87	99
Alkyl- alkoxy silane	79	87	89	76	97

Source: Pfeifer et al., 1981

Table 3. Reduction of Saltwater Absorption after Sealant Application, %

Material	Series I	Series II	Series III
Epoxy	90	91	91
Methyl - methacrylate	78	82	83
Alkyl- alkoxy silane	70	74	79

Source: Pfeifer et al., 1981

From test Series-II, it was concluded that Alkyl-alkoxy silane and methyl methacrylate act as chloride screens irrespective of the number of days of air-drying prior to sealant application. Another test series carried out by Bush (1998), based on NCHRP 244 Series-II, AASHTO T259/T260, and a modified version of ASTM C642, revealed that the depth of penetration depends on the moisture content of concrete at the time of sealant application. ASTM C642 procedure was modified by limiting the sealant application to one surface and waxing all remaining surfaces, thus allowing the penetration only through the treated surface. For his study, Bush (1998) used isobutyltrimethoxysilane and isopropyl alcohol as the water repellent and the carrier, respectively. McGettigan (1992) also mentioned that the substrate moisture content is one of the influential factors in the depth of penetration of sealant. According to ASTM tests, specimens are required to be treated with penetrating sealants and immersed in salt water from an essentially dry state. Therefore, these tests do not represent the field conditions (Bush et al., 1997). To form the water repellent layer on the pore surface, silane/siloxanes require a certain amount of moisture present within concrete. Silane shows adequate performance against moisture ingress regardless of the substrate moisture content at the time of sealant application. But the depth of penetration of sealant is affected by the moisture content of the substrate (Basheer et al., 1997).

Evaporation of penetrating sealants during the field applications was a concern. Evaporation depends on the volatility of penetrating sealants. During field applications, manufacturers recommend flooding the concrete surface. Upon flooding, several actions take place simultaneously: capillary action by which the sealant is drawn into the substrate; reaction of molecules of water repellent with each other and with the substrate; and the evaporation of water repellent. From an experiment conducted using 40-percent isobutyltrimethoxy silane and ethanol as the carrier, McGettigan (1990) concluded that the evaporation was noticeable after about one hour. A large amount of evaporation that occurred was ascribed to the solvent, ethanol. Finally, based on the experiment conducted to simulate the adverse weather conditions (i.e., very high temperature, wind, and solar radiation), it was demonstrated that monomeric alkyl alkoxy silanes were excellent waterproofing agents and only a negligible amount of sealant was lost as a result of evaporation (McGettigan, 1990). However, Polder (1997) stated that, during his experiments, a substantial amount of silane was lost by evaporation.

3.1 NORTH AMERICAN PRACTICE

3.1.1 MDOT Practice

Michigan Department of Transportation (MDOT) conducts experiments for evaluating penetrating-sealer products. MDOT conducted a research project on penetrating sealants about eight years ago, but at this time is performing no experimental field-level applications on concrete bridge decks because of the uncertainties of application protocols and the benefits of penetrating sealants. However, MDOT maintains a list of approved penetrating sealants for sealing concrete surfaces. If a penetrating sealant meets the requirements of NCHRP Report 244, it is added to the Qualified Product List (QPL). To confirm that the product meets NCHRP Report 244 requirements, manufacturers must acquire satisfactory test results of the product from an independent testing laboratory. MDOT does not conduct tests to verify the experimental results submitted by the manufacturer (Miller, T. D., 2001).

3.1.1.1 MDOT Current Practices

MDOT's current focus with regard to sealing bridge deck surface is on epoxy overlays because they provide impermeable layers over the concrete bridge decks. Additionally, the rough surface of epoxy overlays has the ability to trap and hold de-icing salt for a considerably longer duration than other overlays. This property reduces the need for frequent application of de-icing salts. According to MDOT, these epoxy overlays prevent the transfer of water vapor and other gasses, but may not affect the breathability of the concrete because only one surface of the bridge deck is sealed. Literature indicates that prevention of breathability of concrete from any surface adversely affects concrete durability. Because of cost and several other drawbacks of epoxy overlays, MDOT is interested in finding other options for sealing concrete bridge decks (Miller, T. D., 2001).

3.1.1.2 Effect of Concrete Strength on Penetration Depth

Generally, manufacturers provide necessary technical data with the products, including the penetration depths of sealants. But MDOT experiments with several sealants on standard concrete with 28-day specified strength of 4500 psi (MDOT Grade D) have shown that the depths of penetration are less than those specified by the manufacturers. The main reason that manufacturers obtain greater penetration depths is because they use less dense concrete. MDOT Grade-D concrete is specified for most bridge decks. MDOT experiments have shown that the average depth of penetration is about 4-mm, less than the minimum required depth of penetration of 6-mm. Similar comments on specified depth of penetration can be found in published literature (McGettigan, E., 1990 and Cady, 1994). The minimum-penetration-depth requirement is necessary due to wearing of the deck surface and protecting the sealant from ultraviolet (UV) radiation. Since the penetrating sealant is colorless and transparent, it is hard to determine the presence of sealant in the concrete bridge decks by naked eye.

3.1.1.3 Application Procedures

According to MDOT, selection of penetrating sealants is a contractor responsibility only when specified in contract documents. Generally, a contractor selects a penetrating sealant from the qualified product list in which all the products are assumed to be equal in their quality and the performance. Manufacturers' recommendations are followed for surface preparation and application procedures.

3.1.2 Practices of State Highway Agencies in North America

3.1.2.1 Canadian Practice

Alberta Department of Transportation has developed specifications for concrete sealers. These specifications, B388, describe one- or two-component concrete sealer products. In conjunction with B388 specifications, the following documents are used for establishing the concrete-sealer performance:

BT001 - Test Procedure for Measuring the Vapor Transmission, Water Proofing, and Hiding Power of Concrete Sealers.

BT002 - Test Procedures for Alkaline Resistance of Penetrating Sealers for Bridge Concrete Sealer.

BT008 - Test Procedures for Finger Printing Sealers Using Infrared Spectroscopy and Gas Chromatographic Separation.

BT010 - Test Procedures for Casting and Storing of Concrete test Specimens for Use in Approved Testing of Sealers.

In addition to these documents, ASTM D5095 is specified for determining the nonvolatile content in silanes, siloxanes, and silane-siloxane blends that are common chemicals used as penetrating sealants.

Alberta DOT requires that the manufacturers/suppliers contract with independent testing laboratories to perform the tests on sealants in accordance with the B388 specifications before submitting the sealants to the Department for review. Sealers are classified into three types. Type-1 (Appendix B) encompasses penetrating sealants for use on traffic-bearing surfaces exposed to abrasion. Type --1a and Type-1b are used in outdoor conditions such as on bridge decks. All the sealant types are used on both new and rehabilitated structures and have shown good performance (Wong, J., 2002).

In Newfoundland, highway bridges are waterproofed with hot applied rubberized asphalt membrane. Penetrating sealants are used on all concrete subjected to de-icing salts and on the concrete placed between the dates September 1st and April 30th including curbs, barrier walls, end blocks, and decks. Sealant selection criteria are based on NCHRP Report 244 requirements. In addition, the concrete sealer is expected to provide a minimum 75-percent reduction in weight gain and chloride ion content. The sealer must be a clear silane solution with at least 40-percent silane (Appendix B) by weight or concentration and be suitable for application to 28-day-old or older concrete. The sealer should not significantly discolor concrete. Application is carried out strictly in accordance with manufacturer's instructions and guidelines (Lester, P., 2002).

New Brunswick DOT uses penetrating sealants only for particular situations. Selection and application procedures are based on manufacturer's recommendations. High-performance concrete use with corrosion inhibition and waterproofing are the main methods of protection for the concrete decks. It is reported that 15-liters of a calcium nitrite corrosion inhibitor is included in the deck mix (Strang, F., 2002).

In Ontario, most bridge decks are waterproofed with hot-applied rubberized asphaltic membranes. Penetrating sealers are not used on concrete bridge decks. They are occasionally used for barrier walls only when the concrete cover to reinforcement or the quality of concrete is questionable (Lai, D., 2002).

3.1.2.2 U S Practice

Colorado DOT recommends penetrating sealants for all new bare concrete bridge decks. The recommended penetrating sealant consists of an alkyl-alkoxy silane at a concentration of 40-percent solids in water or a high-flash organic solvent. At this time, Colorado DOT does not conduct any tests for sealant qualification. Sealant selection is based on manufacturers' certification. Even though there are specifications for concrete-surface preparation and sealant-application procedures, most conservative procedures are selected after comparing the manufacturers' recommendations. At present, Colorado DOT is experimenting with a modification of deck concrete mix to include 15– to 20-percent fly ash, 3- to 4-percent silica fume, and a water/cement ratio of 0.38 – 0.42, which is intended to have a blend of moderately low permeability, low cracking tendency, good strength, and good workability (Michael, 2002).

Delaware DOT evaluates penetrating sealants on a project-by-project basis. Mainly penetrating methacrylate sealers are specified. Low-permeability concrete, such as latex-modified or silica-fume-modified concrete, is used as deck overlays to reduce the chloride ingress from de-icing salts (Pappas, J., 2002).

Connecticut DOT does not use penetrating sealants for concrete bridge decks. Instead, all bridge decks are overlaid with a 2.5-inch bituminous concrete wearing surface superimposed on a Woven Glass Fabric Membrane (Liberatore, F. R., 2002).

Caltrans uses high-molecular-weight methacrylate to repair cracks in concrete bridge decks. The crack-sealing procedure was initiated in 1985 and has performed very well and extended the life of bridge decks (Michael, J. L., 2002).

Iowa DOT has carried out extensive work on developing a dense concrete overlay as a design treatment to protect concrete bridge decks. With this concrete overlay, Iowa DOT was able to achieve satisfactory performance and estimates significant savings over the years through its use (MacGillivray, I., 2002). Recently, silane has been used to seal the deck cracks on the US- 61/US-151 bridge over the Mississippi River at Dubuque, Iowa (McDonald, N. L., 2002).

Meantime, Minnesota DOT has done extensive studies on prevention of concrete bridge deck cracking and the application of penetrating sealants. The authors do not have specific information related to Minnesota DOT's current practice on penetrating sealants.

3.2 EUROPEAN PRACTICE

To examine the European experience on penetrating sealants, we contacted the following highway authorities, institutions, and companies. Their names, websites, and contacts are given in Table 4.

Table 4. European Countries, Institutions, Websites, and Contacts

Country	Websites	Institution/Company/ Contacts
Netherlands	www.crow.nl	Information and Technology Center for Transport and Infrastructure crow@crow.nl A. J. Van Leest: vanleest@crow.nl
	www.bolidt.nl & www.cur.nl	Special Producer of Membrane Systems
	www.minwenw.nl	Ministry of Transport, Public Works, and Water Management
	www.swov.nl	Institute for Road Safety Research info@swov.nl
Norway	www.sintef.no	Scientific and Industrial Research Institute
	www.vegvesen.no	Directorate of Public Roads J. Krokeburg: jon.krokeburg@vegvesen.no
	www.toi.no	Transportation Institute
Poland	www.its.home.pl	The Motor Transport Institute

Table 4. European Countries, Institutions, Websites, and Contacts (continued)

Country	Websites	Institution/Company/ Contacts
Sweden	www.tfk.se	Transport Research Institute info@tfk.se
	www.swedgeo.se	Swedish Geotechnical Ins.
	www.vti.se	Swedish National Road and Transport Research Ins. K. Gustafson: kent.Gustafson@vti.se
	www.vv.se	Swedish National Road Admin, L. Lindblad: lennart.lindblad@vv.se P. E. Westgren: per-eric.westgren@vv.se
Denmark	www.ifp.dtu.dk/~vt	Technical Univ. of Denmark, Transportation and Construction Department
	www.vd.dk	Danish Road Directorate
Finland	www.tieh.fi	Finnish National Road Administration
	www.vtt.fi	VTT Technical Research Center of Finland
Germany	www.bast.de	Federal Highway Research Institute itrd@bast.de R. Wruck: Wruck@bast.de
England	www.trl.co.uk	Transport Research Library
	www.itctraffic.com	Institution for Traffic Care
	www.imeche.org.uk	British Hydromechanics Research Group

In identifying the contact agencies, we mainly used two search engines: http://www.google.com and http://www.scirus.com. The key words used in this search were *concrete*, *water repellent*, *hydrophobic*, and *impregnants*. From this search, we found many valuable publications.

The same questionnaire was sent to all the authorities inquiring about standards, field applications, testing methods, and their experience with penetrating sealants. Germany, Netherlands, Switzerland, and Sweden replied to our questionnaire.

The European countries' overview was limited to the replies we received to our simple survey and to literature identified through library and internet searches. Literature indicates that many of European local authorities are using sealers for concrete protection (Basheer et al., 1997; Carter, 1994). However, replies to the survey show that the use of penetrating sealants is limited. The common European thinking is that the sealers are insufficient as a single line of defense to protect concrete decks. Most commonly sealers are used as a secondary level for protecting the deck concrete (Figure 1).

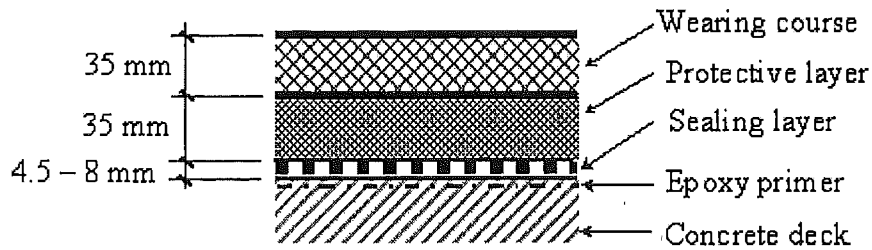


Figure 1. Section of a layered pavement

In 1969, Dynamit Nobel A. G., in West Germany, proposed using alkyl alkoxy silanes as sealers for concrete. Since then, silanes have been used as waterproofing agents in European countries. They are very effective in reducing the ingress of water and salt into concrete. Currently, the finished curb surfaces are required to be treated with silane, siloxane, or epoxy sealers. However, under field conditions, silane did not improve the freeze-thaw durability of concrete (Perenchio, W. F., 1988). Basheer et al., (1997) also mentioned that silane may not be effective in protecting concrete from carbonation and freeze and thaw effects.

Norwegian road authorities indicated that Scandinavian countries have not yet found a hydrophobic product or substance that can penetrate their bridge deck concrete to a depth of several millimeters. They have, however, tested the performance of silane/siloxane agents. Their main concern in the use of penetrating sealants is that the field concrete in Scandinavian climate is never sufficiently dry. Bridge deck concrete with water/cement ratio of 0.40 and silica fume reduces concrete permeability. Further, presence of moisture in relatively dense concrete limits sealer penetration into concrete (Basheer et al., 1997).

Bridge decks in Scandinavian countries are, with few exceptions, protected by a membrane layer and asphalt wearing course (Kompen, R., 2002). Similarly, in Germany, bridge decks are protected from moisture and chloride ions by using polyvinyl chloride or rubberized asphalt membranes (Perenchio, W. F., 1988).

The selection procedure for sealants varies according to country conditions. For instance, the Netherlands DOT includes hydrophobic treatment of bridge decks in its protective procedures and prefers ground granulated blast furnace slag cement in concrete mixtures used for bridges. The purpose of applying this layer is to reduce moisture as well as chloride ingress by 70 to 90 percent (Polder et al., 1997). In another study, extreme weather conditions (that are almost identical to Michigan) were examined, and a general order of effectiveness of the surface treatments against chloride diffusion was defined. Silane and siloxane showed the best performance as penetrating sealants. However, in extreme hot weather, exceeding 113 °F (45 °C), silane/siloxane performed poorly (Jones et al., 1995).

Research performed by the Ministry of Transport, the Netherlands, showed that sealer performance varied with the type of cement, surface finish of concrete, and the type of hydrophobic agent (Polder et al., 1997).

4 SEALERS FOR CONCRETE PROTECTION

Industry provides several types of waterproofing materials for use on concrete surfaces. Most of these materials are silicon based. Currently, major efforts are given to evaluate the performance of penetrating sealants of which the main constituents are silane, siloxane, and silane/siloxane blends. Though there are numerous and varying product qualification testing procedures and criteria are currently used by the various Highway Agencies, a uniform protocol can be developed regarding sealer approval and use. Qualification tests in most cases are not sufficient to properly screen sealer products. Since there are no national standard testing protocols, it is possible to have a high degree of variability reported in qualifying concrete sealers that are approved by the Highway Agencies (Cady, 1994). Some of the variability in field performance among sealer generic types (and even among products comprising the same generic types) may be a result of improper surface preparation or application of sealers. The functional requirements of an acceptable waterproofing penetrating sealant are: resistance to water absorption, measurable depth of penetration, screening of water soluble salts (chlorides), non-staining of treated surface areas, long term stability in an alkaline environment, and low environmental and health risks. Most of the surface sealers deteriorate due to UV radiation, but penetrating to the substrate protects the alkyl group of these penetrating sealants (McGettigan, 1992). Greater depth of penetration provides better protection to concrete and the sealant itself, especially in concrete bridge decks where a larger surface area is exposed to UV radiation as well as vehicular abrasion (Basheer et al., 1997). The main reason for applying a penetrating sealant is to prevent or retard the ingress of chlorides. To achieve this goal, the testing procedures need to address field exposure variables.

4.1 CONCRETE SEALING MATERIALS

Table 5 lists the penetrating sealant products that are approved or used by Highway Agencies as water repellents and pore blockers. Values in this table show the percentages of products that belong to the respective sealer generic type, according to the survey conducted for NCHRP Synthesis 209 (Cady, 1994).

Table 5. Penetrating Sealers

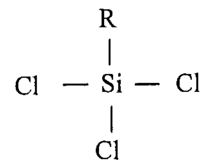
Sealer Generic Type	Products (%)
Silane	24
Siloxane	14
Silane/Siloxane mix	3
Silicone	1
Silicate	5
Epoxy Sealers	27
Synthetic Gum Resins	2
Linseed Oil	4
Stearates	1
Acrylic Sealers	17
Urethane; Polyurethane	1
Polyester	1

Source: Cady, 1994

4.1.1 Silane & Siloxane Penetrating Sealants

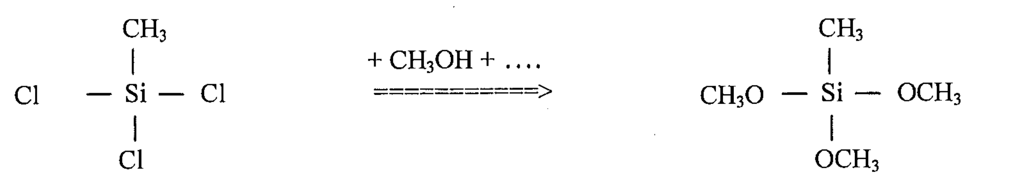
Penetrating sealants are classified as water repellents and pore blockers. Pore blockers do not penetrate as deeply as water repellents due to their larger molecular size (Cady, 1994). Since there is a possibility of wearing off the sealed surface due to abrasion of vehicular traffic as well as exposure to UV radiation, water repellents are more preferred for sealing concrete bridge decks than pore blockers. Water repellents are mainly produced using silanes and siloxanes.

Silicon compounds such as silanes and siloxanes can be divided into two broad classes - monomers and polymers. Silanes, which are monomers, have only one silicon atom. Siloxanes can have longer chains consisting of several repetitive units of silane monomers. Siloxanes that have shorter chains (up to five silicon atoms) can be used as penetrating sealants and are generally referred as "oligomerous" siloxanes. Siloxanes having more than five units (longer chains) are referred as "polymeric" siloxanes. Further, silanes and siloxanes are named based on the molecules that are attached to the silicon atoms. Silanes and siloxanes are produced from the same raw material – chlorosilane.

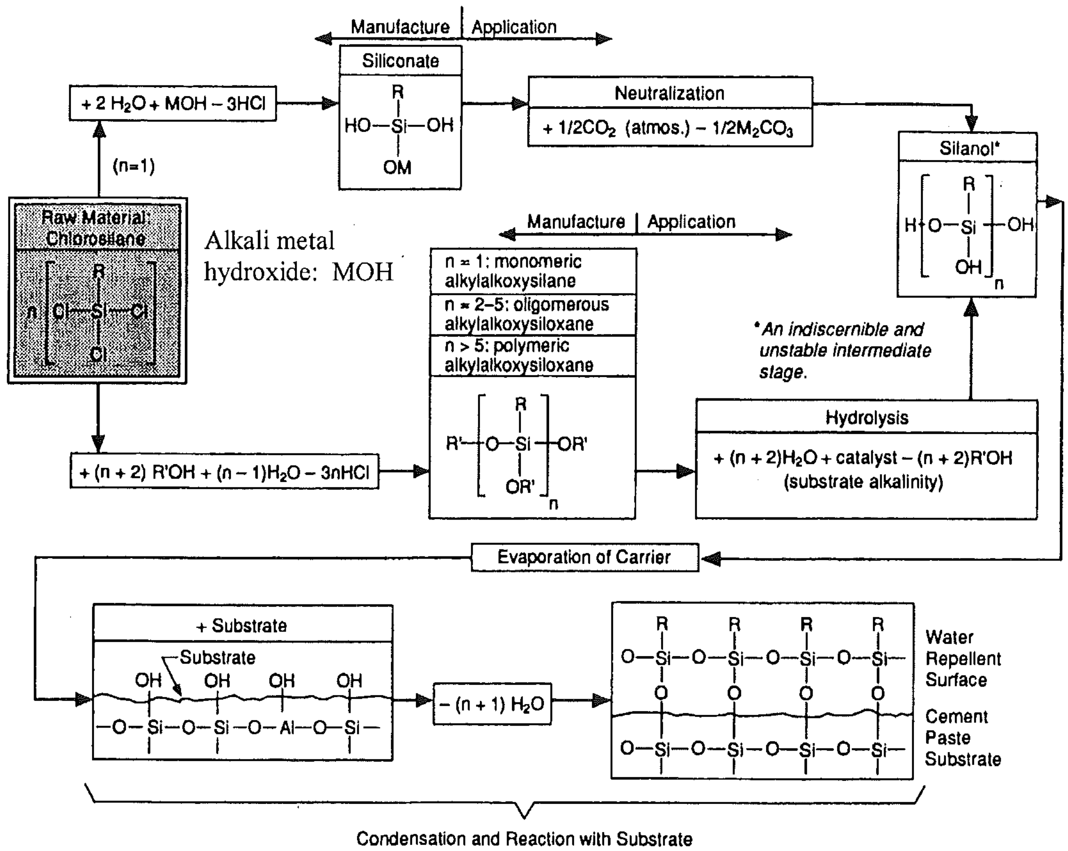


In chlorosilane three chlorine atoms are attached to a silicon atom. During the manufacturing process of silanes and siloxanes, hydrolysable groups known as silicon functional groups replace these chlorine atoms. The organofunctional group (R) is an organic hydrocarbon group having a straight- or branched-chain structure. The silicon functional groups are responsible for the reactivity with siliceous substrate. The exposed organofunctional groups provide a hydrophobic layer on pore walls. Therefore, these silicon compounds fall into the water repellent class of concrete sealers (Cady, 1994).

Silanes and siloxanes are the main constituents in most of the penetrating sealants available on the market. During the manufacturing process, they follow the same general chemical reaction as shown along the lower branch of the flow diagram (Figure 2) starting from chlorosilane. As an example, if methyltrichlorosilane and methyl alcohol (methanol—CH_3OH) are used in the manufacturing process, three moles of alcohol are combined with one mole of chlorosilane (CH_3O- => Cl) to form one mole of methyltrimethoxysilane:



Methyltrichlorosilane   Methyltrimethoxysilane



Source: (Cady, 1994).

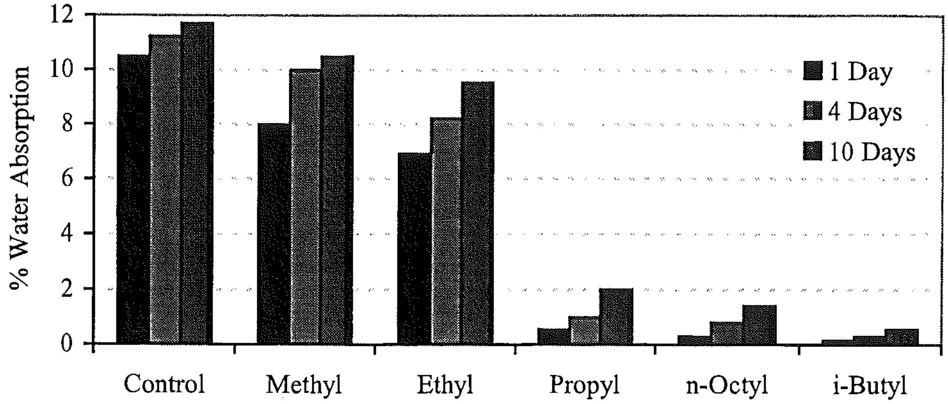
Figure 2. Reaction involved in the manufacture and application of organosilicon compounds (silane, siloxanes, and siliconates)

The specific chemical name of these silicon compounds depends on the silicon functional groups and the organofunctional groups. The organofunctional group and the silicon functional groups are referred as alkyl and alkoxy groups, respectively. Therefore, this class of substance is named alkyl trialkoxy silane. The nature of the organofunctional group determines its degree of water repellency, while penetrability primarily depends on the size of the silicon functional groups (Cady, 1994).

The solvent used in sealant application is intended to have three functions: to form a stable solution, to spread the active ingredients uniformly over the concrete surface, and to allow active ingredients to penetrate into the substrate. The carrier or the solvent, which facilitates the penetrating sealant's active ingredients' seepage into the concrete substrate, evaporates while it penetrates. The active substances in silane or siloxane react with the moisture present within the concrete pore system. During this process, one mole of silanol and three moles of alcohol of the same variety used in the manufacture of the silane are produced. A highly alkaline environment is required for this hydrolysis reaction. Due to its high alkalinity, the concrete substrate provides this favorable environment. After this unstable silanol reacts with itself and with the hydrated cement paste substrate, the protruding organofunctional groups in the chemically bonded lining on the pore surfaces of the concrete yield the water repellency property. This process is depicted in Figure 2.

The manufacturing process of siloxane is almost the same as silane. The only difference is that water is added during the manufacturing process to produce siloxanes from chlorosilane (Figure 2). Even though larger molecular sizes of "oligomerous" siloxanes result in lesser depth of penetration, the chemical reaction with moisture within the concrete is exactly the same as that of silanes. Polymeric siloxanes are suitable only as non-penetrating, pore blocking surface coatings (Cady, 1994).

The reduction of water ingress into concrete is achieved through the chemical bonding of hydrocarbon molecule (alkyl or organofunctional group) in water repellents to the substrate. The surface tension of concrete is reduced due to this bonding. Reduction in surface tension depends on the organofunctional group in silanes or siloxanes. Surface becomes water repellent when the surface tension of concrete is less than that of water (McGettigan, 1992). Figure 3 shows the effects on water absorption of a few organofunctional groups in the most commonly used penetrating sealants. Methyl (CH_3-), ethyl (CH_3CH_2-), propyl ($CH_3CH_2CH_2$-), n-octyl (C_8H_{17}-), and i-butyl ($(CH_3)_2CHCH_2$-) were the organofunctional groups used in this test. High molecular weight iso-butyl and n-octyl groups reduce water ingress more than the relatively smaller groups like methyl and ethyl. The size and structure of the organofunctional group determines the degree of hydrophobicity to a substrate. Larger organofunctional groups furnish higher degrees of hydrophobicity to the concrete substrate. A branched structure of alkyl group is the most preferred when compared with straight chain and cyclic structures. Of all these structure types, the cyclic structure of alkyl group imparts the least hydrophobicity to the substrate (McGettigan, 1992).

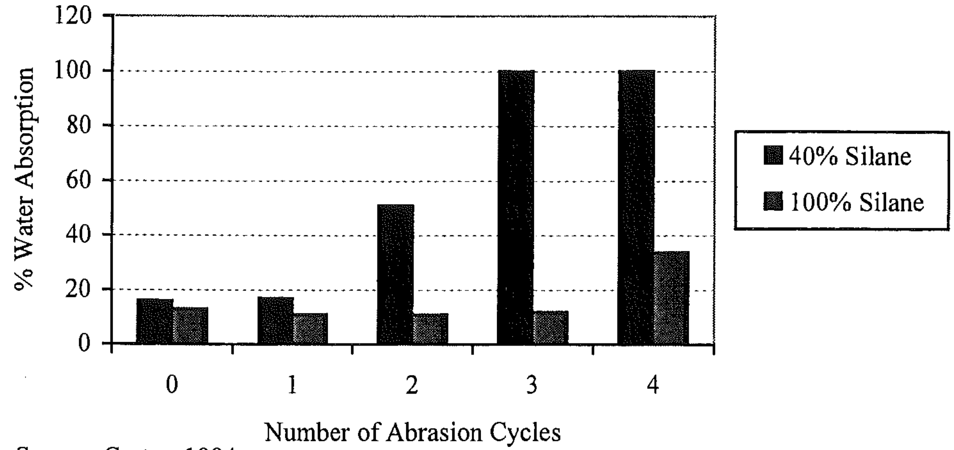


Source: McGettigan, 1992

Figure 3. Water absorption of specimens after sealant application

Molecular size of penetrating sealant establishes the range of pore sizes in concrete that can be treated and the sealants' depth of penetration. Molecular size of silanes (10 to 15 Angstrom units) and siloxanes (25 to 75 Angstrom units) are small enough to enter the pores in concrete (45 to 1000 Angstrom units). Once sealants penetrate concrete pores, the molecules of silane or siloxane become larger (double, triple, or even quadruple) by hydrolysis and condensation, thus limiting further penetration.

Most of the time, alcohol is used as a carrier for sealants. Alcohol solvents have low surface tension, and they are miscible with water, which reduces the effect of moisture in the substrate. Since it is possible to optimize the chemical and physical properties (such as viscosity, contact angle, molecular size, and hydrolysis rate) of certain classes of neat (solvent free) silanes or siloxanes, they can achieve two to three times greater penetration depths than solvent borne silane or siloxanes can. Out of these sealants, certain classes of neat silanes are the best penetrating products (McGettigan, 1992). Using the test procedure recommended by AT&U, Carter (1994) conformed the effectiveness of neat silanes against solvent-based silane sealers. For this test, iso-butyltrimethoxy silane (IBTMOS) was used, and the results are illustrated in Figure 4. If the sealants are solvent based, then, after the carrier evaporates, sealants become more viscous, causing difficulty in penetration. For this reason, neat silanes are preferred because their rate of evaporation is lower. As neat silanes coat the pore walls, leftovers progress deeper into the pores of concrete, giving greater penetration depth than solvent-based silanes do (Carter, 1994).



Source: Carter, 1994

Figure 4. Concentration effects of IBTMOS on water-repellency performance, w/c=0.5

4.1.2 Crack Sealants

High molecular weight methacrylate resins are used by several Highway Agencies for sealing cracks in concrete decks. Caltrans has applied HMWM since 1985 and is satisfied with the performance, to date. Caltrans maintains its own specifications and testing procedures for selecting crack sealants (Michael, J. L., 2002). Iowa DOT has used HMWM to seal the deck of US-136 bridge over the Mississippi River at Keokuk, Iowa (McDonald, N. L., 2002). Iowa's special provision for HMWM has been developed using Caltrans' specification for high molecular weight methacrylate bridge deck treatment (Marks, V.J., 1987).

High-modulus HMWM was unable to penetrate sufficiently into the deck cracks. Cracks appeared again over or near the top of the treated deck cracks. The treated cracks were full depth cracks with width from about 0.004- to 0.010-inches. With a low-modulus HMWM, re-cracking was prevented. These HMWM resins could reduce the amount of water and chloride ion ingress but were not considered as a reliable sealant due to lack of significant penetration and crack filling (Wiss, 1999).

Based on laboratory studies, Wiss (1999) concluded that silane sealers are effective in preventing the corrosion of embedded reinforcement in concrete having 0.012-inches wide cracks. As usual, silane coats the crack walls and the debris in the cracks, making them water repellent. But it is uncertain whether silane sealers are effective in sealing the cracks when bridge decks are subjected to service loads and deflections (Wiss, 1999).

HMWM resins can be used to treat the cracks ranging from 0.001- to 0.08-inches, and it's possible to treat even finer cracks with low-viscosity resins (ACI 224.1R, 2001). For new decks, it is better to treat the early age cracks at least after six months because most of the initial shrinkage cracks occur during the first six months after concrete placement. Silane and siloxane penetrating sealers work on finer cracks of widths less than 0.002-inches. Since silane sealers are compatible with HMWM, it is possible to treat the cracks after applying the silane sealers. Broadcast of sand after HMWM application is necessary to keep the skid resistance of the deck surface (Krauss, 1996).

4.2 SEALER PERFORMANCE

Laboratory and field evaluations of sealer performance characteristically show high variability not only among but also within generic sealer groups. It is also evident, however, that sealer performance is sensitive to environment, substrate, sealer chemical properties, and application variables (Cady, 1994). From a series of tests conducted at laboratory level to simulate the effects of a few of the expected field conditions, such as concrete mix design, concrete surface conditions, curing, and surface preparation procedures prior to silane application, Bush et al., (1997) concluded that direct field measurements are the best methods to evaluate sealer performance. For the test series, isobutyltrimethoxysilane and isopropyl alcohol were used as penetrating sealant and carrier, respectively. Based on the inspection results of 37 bridges in Ohio, Oklahoma, and Rhineland, West Germany that were entirely or partially treated with a 40-percent solution of isobutyltrimethoxysilane and ethyl alcohol carrier, Perenchio (1988) concluded that silane does not affect the freeze-thaw durability of concrete. Carter (1994) mentioned that silane treated concrete in Alberta underwent several freezing and thawing cycles and wetting and drying cycles but did not show any evidence of reduced resistance to freezing and thawing even in the presence of deicing salts.

Depth of penetration, which is generally overstated by sealer manufacturers, is a key parameter in evaluating the performance of penetrating sealants (Cady, 1994; McGettigan, 1992). An additional reason for assuring a depth of penetration is the need to protect the alkyl group of the silane and siloxane from UV radiation. Understanding the difference between "visible penetration" and "working penetration" is necessary to evaluate the sealer performance. Splitting the concrete specimen and measuring the non-wetting band measure visible penetration (Figure 5). Obtaining measurements based on splitting the specimens and moistening the broken surface is a simple but destructive process which requires coring of the deck. Measurement by neutron radiography also requires coring of the deck to observe the depth of visible penetration (Figure 6).

Working, or effective depth of penetration can be measured using the test procedure recommended by AT&U. This test requires sandblasting the specimen surfaces. The limitations for the weight of material removed are established as per face and per cube. Immersing the test cubes in water and measuring the weight gain determine waterproofing performance after surface abrasion. To study the performance of silane and siloxane sealers after abrasion, McGettigan (1992) employed AT&U test procedure by removing a 1-mm thick layer from the treated surface. Figure 7 shows the effectiveness of silane and siloxane water repellents before and after abrasion. It is preferable that the effects of a sealant's water repellent properties be consistent along the various levels of its penetration depth; this is known as "uniform gradient permeation (UGP)". The factors affecting UGP are rate of hydrolysis and condensation, molecular size, physical properties, and amount of sealant. Solvent free (neat) silane products acquire the greatest level of UGP. Generally a 40-percent silane solution shows greater UGP than a 20-percent silane, or a 10-percent siloxane solution (McGettigan, 1992). Figure 8 shows the performance of neat silane sealer after several abrasion cycles. For the test results depicted in Figure 8 and Figure 9, an abrasion cycle is defined as the employment of AT&U sandblasting procedure once on the specimens and measuring waterproofing performance. For better performance of penetrating sealants, more than one application is required (Nolan et al., 1995; Jones et al., 1994; and Basheer et al., 1997). In the experimental program conducted to study the influence of concrete's moisture condition on the performance of surface treatments, Basheer et al., (1997) maintained a four-hour minimum drying period between each application. To obtain better penetration depths from reapplications, the interval between each application should be determined based on the prevailing weather conditions. Previously treated substrate absorbs less water than it releases as water vapor. Therefore, the substrate becomes drier and absorbs more sealants, resulting in greater penetration depths (Carter, 1994). Figure 9 shows the results of an experiment that was carried out using concrete cubes of 0.5-w/c ratio with four reapplications of 40-percent n-octyltriethoxy silane (NOTEOS) in propanol.

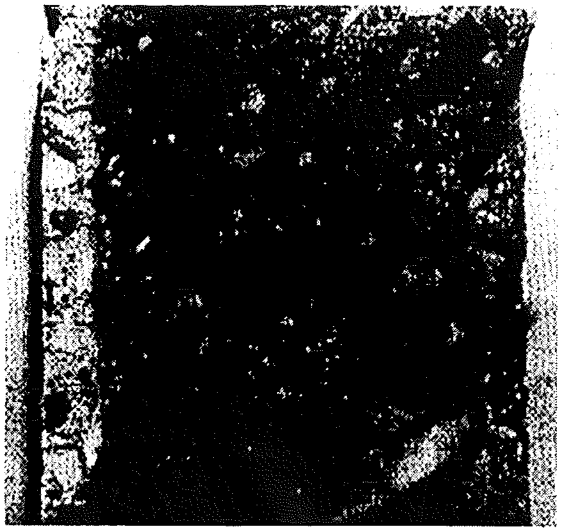
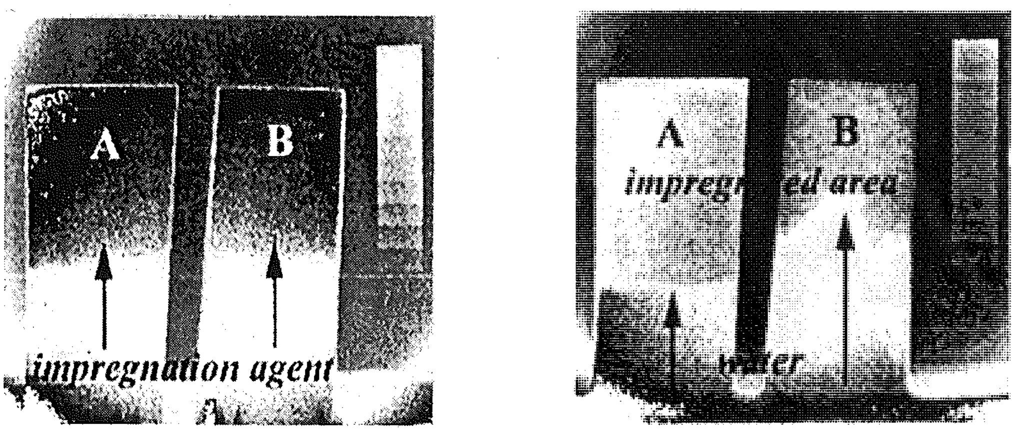
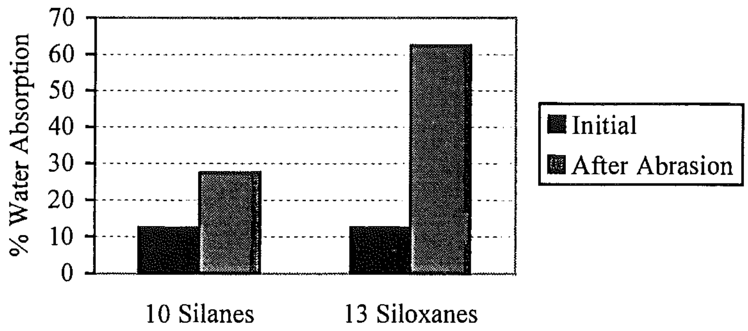


Figure 5. Split specimen after wetting with the hydrophobic side on left



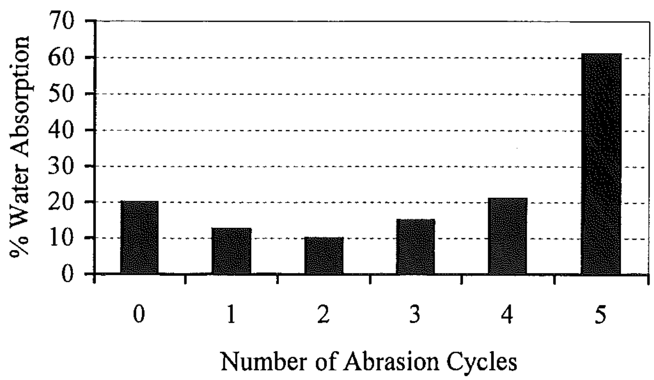
(a) (b)

Figure 6. (a) Penetration of hydrophobic impregnation agents into clay brick samples (2-cm thick) and (b) penetration of moisture into the impregnated area of the samples



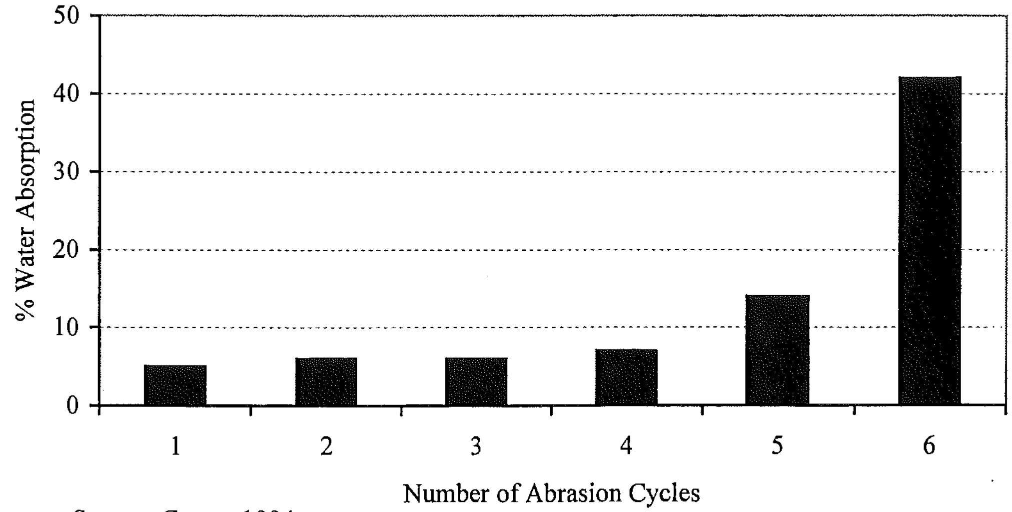
Source: McGettigan, 1992

Figure 7. Average water-exclusion values of silane and siloxane water repellents, before and after abrasion



Source: McGettigan, 1992

Figure 8. Performance of neat silane using the AT&U test method with repeated abrasion cycles



Source: Carter, 1994

Figure 9. Water-repellency performance of 0.5 w/c test cubes sealed five times with 40-percent NOTEOS in propanol

Another popular method of evaluating relative performance of the hydrophobic treatments is the electrical resistivity method. This test method is used to measure surface resistivity that indicates the functioning of sealers as hydrophobic agents. It is possible to implement this method in laboratories as well as in the field. There are many modified electrical resistivity methods but the most common method is the Wenner four-probe resistivity measurement method (Chatelut et al., and McCarter, 1996). Conduction of currents between electrodes occurs through continuous water-filled pores. After sealants are applied, a continuous path for electrical conduction, near the surface, may not exist. Therefore, surface resistivity of treated concrete is greater than that of untreated concrete. Distance between electrodes is determined based on the sample size to avoid edge effects as well as the desired depth of penetration of electrical currents. Greater spacing between electrodes will reflect the resistance of the body of unsealed concrete because a very shallow thickness is affected by the penetrating sealer (Whiting et al., 1992). Contact between electrodes and the concrete surface can be made using spots of conductive paints. Surface resistivity values can be varied depending on the ionic concentration of pore water (McCarter, 1996).

This method is based on the measurement of electrical resistivity (ρ) with the four-electrode probe (ABCD) (Figure 10). The constant current (I) is applied to two outer electrodes

(A&D) and the arising difference of potential (ΔV) is measured between two inner electrodes (B&C).

$$\rho = 2\pi a \Delta v / I \quad (1)$$

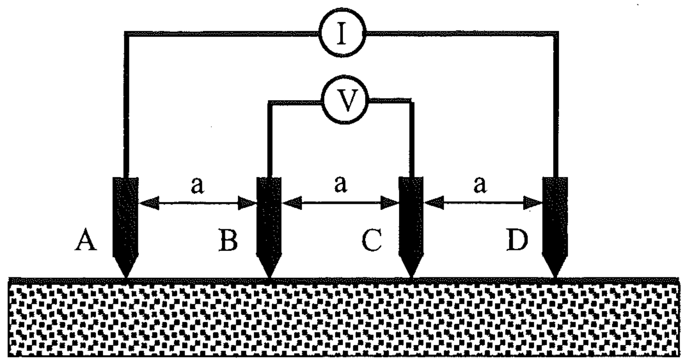


Figure 10. Schematic of Wenner four-probe resistivity measurement method

Cady (1993) proposed a test procedure for determining the relative effectiveness of penetrating sealers. It requires the use of a model 400 solid-state 4-pin soil-resistance meter from Nilsson Electrical Laboratory, Inc. He proposed to use a 2-pin mode instead of the generally accepted 4-pin mode. Based on his test results, he proposed resistance values for evaluating the effectiveness of penetrating sealants (Table 6). These values are based on a current supply with a carrier frequency of 100 Hz. According to the instruction manual of the proposed soil resistance meter, the reading obtained using the 2-pin mode includes the resistance of the two probes, concrete resistance between them, and the resistance of any cables from the connections to the probes.

Table 6. Categories of Relative Effectiveness of Sealers

100 Hz Resistance (kiloohms)	Relative Effectiveness of Sealer (Category)
0 to 200	Ineffective (or not sealed)
200 to 400	Borderline effective
Over 400	Effective

Source: Cady, 1993

4.3 SURFACE PREPARATION & APPLICATION PROCEDURES

Surface preparation for penetrating sealants is critical in order to achieve better penetration depths. According to manufacturers' recommendations as well as data published in the literature, concrete must be at least 28 days old. The surface must be clean, dry, open capillary, structurally sound, and free of curing compounds and contaminants. When the concrete bridge deck is more than one year old and silane or siloxane sealant is going to be applied for the first time, the carbonated layer formed at the surface of the concrete must be removed (Cady, 1994). Bridge decks that were previously exposed to vehicular traffic should be cleaned to remove oil, grease, rubber, and other organic contaminants present on the deck surface. Alberta DOT uses high-pressure water blasts on the bridge decks on a yearly basis. The decks that are on the four-year sealing cycle are sealed two days after water blasting (Jim, W., 2002). A 2-day drying period is recommended by most of the manufacturers and Highway Agencies. This period can be varied based on prevailing weather conditions.

In most cases, application procedures are based on manufacturers' recommendations. Table 7 shows the recommended methods for application of silane and siloxane sealers in the survey conducted for NCHRP Synthesis 209. Survey responses indicate that roller, air-less spray, and broom are the preferred methods for silane; for siloxane, air-less spray and roller are preferred. Manual and automatic air-less spray guns are available on the market. The nozzle of this equipment atomizes the sealants at low pressures, achieving a controllable spray that results in minimal overspray. Several manufacturers and Highway Agencies recommend garden sprayer for sealant application. Surface flooding is also another preferred method, provided that necessary steps have been taken to prevent the runoff of the sealants.

Table 7. Recommended Application Methods

Sealer Generic Type	Number of Products	Method Recommended, % of products					
		Squeegee	Roller	Broom	Spray		Other*
					Air	Air-less	
Silanes	22	36	91	77	45	86	0
Siloxanes	13	38	69	46	46	77	8

* Low-pressure pump; flooding
Source: Cady, 1994

5 PERMEABILITY OF CONCRETE CONTROLLING SEALANT PENETRATION

5.1 THEORETICAL FUNDAMENTALS

5.1.1 Formulation of Sealant Impregnation

To formulate the penetration of sealants into concrete, the theoretical fundamentals of transport through porous medium need to be defined. With the proper description of the flow phenomenon and the effective factors, reasonably accurate estimations of the depth of penetration can be made.

The formulation described below for sealant penetration into concrete is derived for cylindrical specimens to avoid edge/corner effects. The side of the cylinder is coated, and flow is only through the top surface (Figure 11).

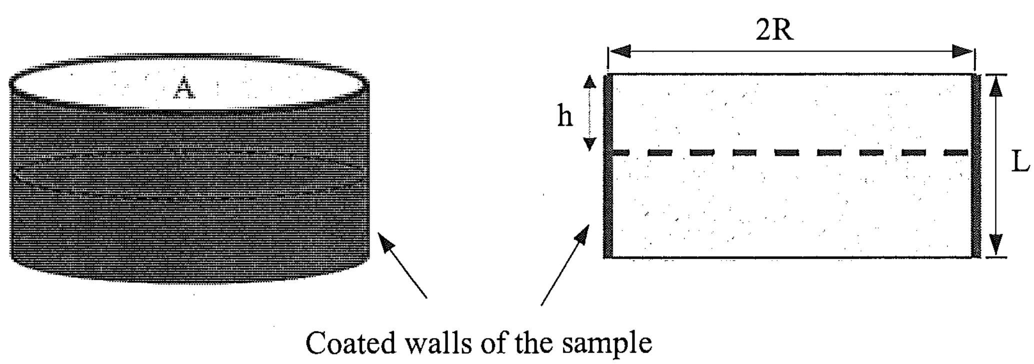


Figure 11. Sample for the impregnation formulation

One can derive a relationship for material permeability from the knowledge of the properties of the porous network (Reynes et al., 2001). Assuming steady flow within the porous network, Darcy's law for a small-impregnated volume is given thus:

$$dV_{imp} = \frac{k}{\eta} A \frac{\Delta P}{h(t)} dt \qquad (2)$$

Where dV_{imp} is the impregnated volume within a time interval of dt, k is the intrinsic permeability coefficient that will be called "permeability coefficient" in this report, A is the area normal to the surface of flow, η is the dynamic viscosity, and $\Delta P / h(t)$ is the pressure gradient in the liquid.

dV_{imp} is also expressed in terms of the porosity (p) and the depth of impregnation (h) as

$$dV_{imp} = pAdh \tag{3}$$

From (2) and (3), we find

$$h(t)dh = \frac{k}{\eta}\frac{1}{p}\Delta P dt, \tag{4}$$

and, using the boundary condition h (0) = 0, and integrating

$$h^2 = \frac{2k}{\eta}\frac{1}{p}\Delta P t. \tag{5}$$

Capillary forces are the driving forces for fluid migration. ΔP is the differential capillary pressure, which can be expressed as:

$$\Delta P = \frac{2\gamma \cos\theta}{a} \tag{6}$$

Where a is the pore radius of the cylindrical capillary, γ is the surface tension, and θ is the contact angle.

Substituting Eq. 6 into Eq. 5,

$$h^2 = \frac{4k}{\eta}\frac{\gamma}{p}\frac{\cos\theta}{a}t \tag{7}$$

$$\text{or} \quad h^2 = \alpha t \tag{8}$$

where

$$\alpha = 4\frac{\gamma}{\eta}\frac{k}{pa}\mathrm{Cos}\theta \tag{8a}$$

represents the slope between square of depth of penetration (h^2) and penetration duration (t).

Solving Eq. 8(a) for the permeability coefficient, we obtain

$$k = \alpha.p.a\frac{\eta}{4Cos\theta}\frac{1}{\gamma} \tag{9}$$

According to Eq. 9, permeability coefficient, which defines the sealant penetration, can be determined from specific concrete properties (porosity and mean pore radius) and sealant properties (viscosity, surface tension, and contact angle). In addition to these properties tortuosity of the pore structure and the pore surface topology will affect the permeability coefficient. In Eq. 9, α incorporates these effects and can be determined from an impregnation experiment by plotting h^2 vs t. Meantime, intrinsic permeability of concrete can also be determined by using direct permeability tests (e.g., a gas permeability test, etc.).

Table 8. Factors Controlling the Depth of Penetration of Sealants

Concrete	Penetrating Sealants	Other
Pore size	Viscosity	Temperature
Pore distribution	Contact angle	Relative humidity
Moisture	Surface tension	Application pressure
Age	Molecular size	
Admixtures	Molecular weight	
Crack width and density		

5.1.2 Numerical Example

In order to demonstrate the use of Eq. 7, a case is investigated where the concrete deck surface is flooded with water. The formulation derived above is used in calculating the depth of penetration of water against time. In this example the following concrete and fluid properties are used:

Surface tension of water (γ) @ 68 F	= 4.15×10^{-5} lbf/in
Viscosity of water (η) @ 68 F	= 1.45×10^{-7} lbf-s/in
Concrete mean pore radius (a)	= 6×10^{-7} in (150 Angstrom units)
Contact angle of water on concrete (θ)	= 49.5 deg.
Density of water @ 68 F	= 3.61×10^{-2} lb/in^3
Density of nitrogen	= 4.34×10^{-3} lb/in^3
Viscosity of nitrogen	= 2.58×10^{-9} lbf-s/in

The porosity and intrinsic permeability of concrete used in this example are values measured on typical bridge deck concrete used on several deck replacement projects (Yaman et al., 2001). These measurements are shown in Table 9.

Table 9. Porosity and Intrinsic Permeability Values of Bridge Deck Concrete (28-Day)

Bridge ID	Porosity (%)	Intrinsic Permeability (in^2 x 10^{-12})	Permeability (in/s x 10^{-7})	
		Gas	Gas	Water
B1	10.58	7.52	126.00	18.60
B2	9.84	3.33	56.00	8.30
B3	10.67	2.32	39.00	5.79
B4	8.81	0.53	8.85	1.31
B5	8.72	0.37	6.25	0.93

Source: Yaman et al., 2001

From Eq. 7, depth of penetration against time is calculated and shown in Table 10 as the depth of penetration of water at 5-second time intervals.

Table 10. Water Penetration Depth in Bridge Decks

Time (s)	Water Penetration Depth (in)				
	B1	B2	B3	B4	B5
0	0.00	0.00	0.00	0.00	0.00
5	0.67	0.46	0.37	0.19	0.16
10	0.95	0.65	0.52	0.27	0.23
15	1.16	0.80	0.64	0.34	0.28
20	1.34	0.92	0.74	0.39	0.33
25	1.50	1.03	0.83	0.43	0.37
30	1.64	1.13	0.91	0.48	0.40

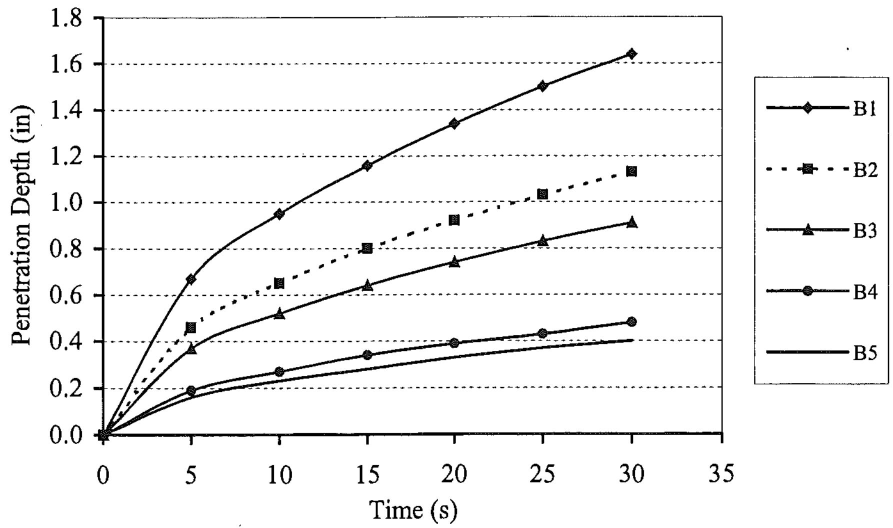


Figure 12. Water penetration depth on various bridge decks

This example depicts the application of fundamental equations and the variation of permeability values that cause different depths of penetrations among bridge decks. The penetration depths in Figure 12 will be more than those achieved under normal conditions. This is mainly due to the assumptions made during the derivations of the equations and to other unaccounted factors (reactivity with concrete, presence of moisture within concrete, relative humidity, etc). One can also set up experiments to determine the depth of penetration which do incorporate the unaccounted factors. Meantime, by knowing the impregnated volume through a single face and the dimensions of that face of the specimen, one can calculate the sealant application rate. The procedure for calculating rate of sealant application is described in AT&U document BT 001 – *Test Procedure for Measuring the Vapor Transmission, Waterproofing, and Hiding Power of Concrete Sealers.*

For this example, water is used as the penetrant to demonstrate the calculation procedures, but any kind of liquid can be used, provided its required properties are known.

5.2 CONCRETE PERMEABILITY PROPERTIES

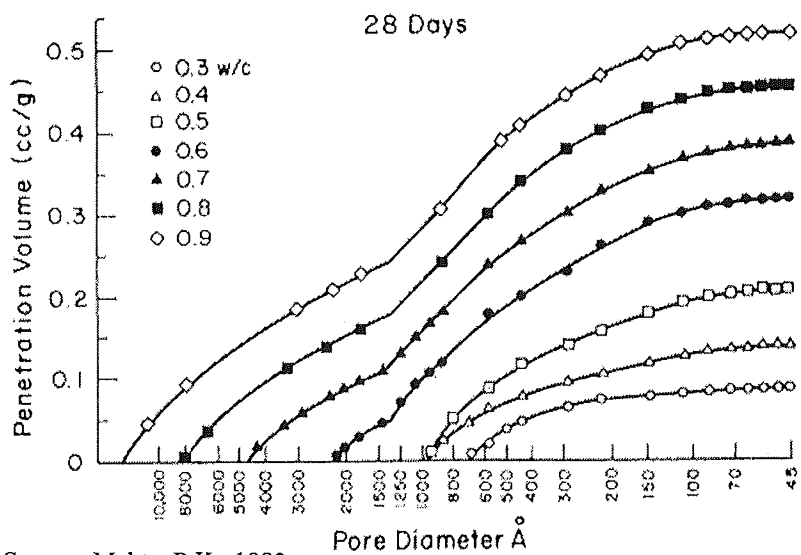
Flow into concrete is primarily through the capillary pores. Much smaller cement gel pores contribute to the permeability of concrete, but the cement paste as a whole is 20 to 100 times more permeable than the gel itself. Therefore, the permeability of hardened cement paste is primarily controlled by its capillary porosity (Neville, 1995). For 28 day old concrete, with w/c ratio ranges from 0.4 ~0.5, diameter of capillary pores varies from 45 to 1000 Angstrom units (Figure 13).

From Figure 14 it can be seen that a reduction of w/c ratio lowers the coefficient of permeability by a large magnitude. At a w/c ratio of 0.45, the permeability coefficient is typically $4x10^{-10}$ or $4x10^{-11}$-inches/second. These coefficients have been calculated by allowing water to permeate through concrete (Neville, 1995). In bridge deck concrete, the most common w/c ratio is between 0.40 - 0.45 (Yaman et al., 2001). The permeability of cement paste varies with the progress of hydration (Figure 15). Drying of the cement paste increases its permeability, because shrinkage initiates cracking of the gel between the capillaries, thus opening new passages to water (Neville, 1995).

A typical pore-size distribution plot of several specimens tested by the mercury intrusion technique is shown in Figure 13. It was documented that it is not the total porosity but the pore-size distribution that actually controls permeability and volume change in a hardened cement paste. Pore-size distribution is affected by the w/c ratio and the age (degree) of cement hydration (Mehta and Monteiro, 1993). The typical sizes of both the solid phases and the voids in a hydrated cement paste are shown in Figure 16.

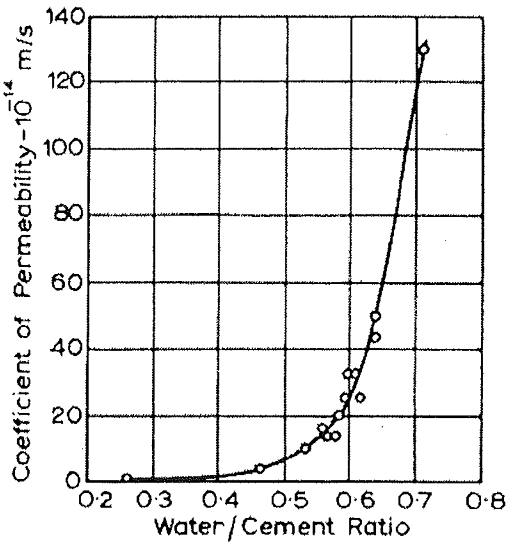
Table 11. Relation Between Pore Distribution and Pore Volume for w/c = 0.4 at 28-Day

Pore diameter, 10^{-6} in.	Pore volume, %
4.0 – 2.4	21
2.4 – 1.2	29
1.2 – 0.18	50



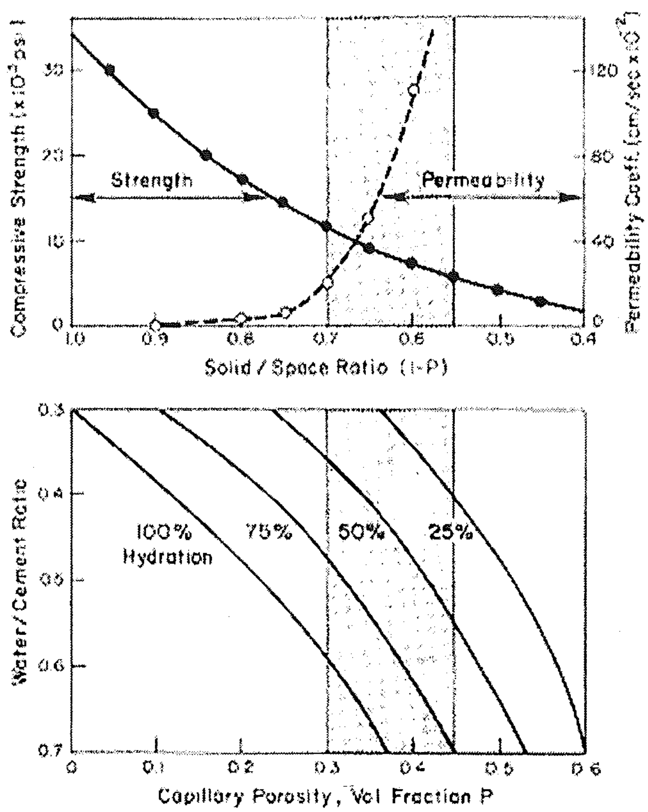
Source: Mehta, P.K., 1993

Figure 13. Pore-size distribution in hydrated cement pastes



Source: Neville, A.M., 1995

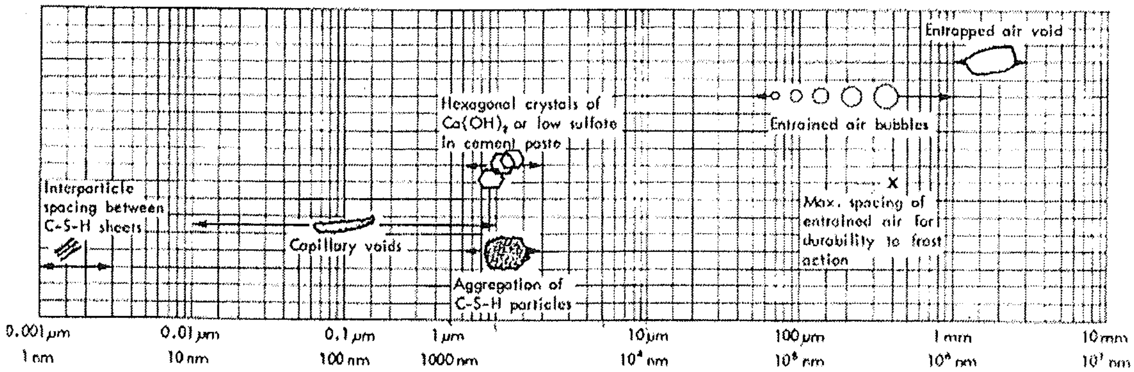
Figure 14. Relation between permeability and w/c ratio for mature cement pastes (93 percent of cement hydrated)



Source: Mehta, P.K., 1993

Figure 15. Influence of w/c ratio and degree of hydration on strength and permeability

(The shaded area shows the typical capillary porosity range in hydrated cement pastes.)



Source: Mehta, P.K., 1993

Figure 16. Dimensional range of solids and pores in a hydrated cement paste

5.3 PERMEABILITY PROPERTIES OF CRACKED CONCRETE

Cracking of concrete is described as an inevitable phenomenon. In this study, the primary interest is on decks cracked at an early age. This can again be categorized as early age cracked concrete due to drying shrinkage, applied loads, and thermal effects. Since early age cracks are very narrow, it is impractical to treat the cracks individually. Therefore, use of penetrating sealants can be a good solution for reducing the permeability of concrete with early age cracks. Certain sealant materials appear to offer added corrosion protection to embedded steel when cracks are present. This fact would suggest that cracks in such members could be given multiple coats of these sealers to achieve even better corrosion protection performance (Pfeifer et al., 1981). Several State Highway Agencies use high molecular weight methacrylate to seal cracks. To find the suitable types of penetrating sealants that can be used as crack sealants, one must understand the various crack types and their sizes. A brief review of the types and causes of cracking according to Neville (1995) follows below.

If the amount of water lost per unit area exceeds the amount of water brought to the surface by bleeding, surface cracking occurs. This is known as *plastic shrinkage cracking*. Plastic shrinkage and plastic settlement cracking occur in fresh concrete. Plastic shrinkage cracks can be deep range in widths between 0.004- and 0.12-inches, with crack lengths of less than three feet. Typical plastic shrinkage cracks are parallel to one another, spaced one to three feet apart.

Another type of cracking on the surface of fresh concrete is caused by differential settlement of plastic concrete due to obstructions, such as large aggregate particles or reinforcing bars. This *plastic settlement cracking* can be avoided by the use of a dry mix, good compaction, and by limiting the rate of build-up of concrete.

Another type of early cracking, known as *crazing,* occurs on slabs when the concrete surface has higher water content than its interior. The pattern of crazing looks like an irregular network of cracks with a spacing of up to about 4-inches. The cracks are very shallow and develop early but may not be noticed until etched by dirt.

In addition, a different type of surface damage, known as *blister*, can occur if bleed water or large air bubbles are trapped just below the surface of the concrete by a thin layer of laitance induced while finishing. Blisters are 0.5- to 4-inches in diameter and 0.0625- to 0.5-inches thick.

In hardened concrete, cracking may be caused by drying shrinkage or by restrained early age thermal movement. Loss of moisture from hardened concrete is the cause of drying shrinkage (Neville and Brooks, 1987).

Tolerable crack width for concrete in the environment of deicing chemicals is generally specified as 0.007-inches (ACI Committee 224, 2001). The early age cracking does not adversely influence the strength and serviceability of concrete members but reduces freeze and thaw durability. The cracks allow more water penetration than uncracked concrete allows. This water ingress cause saturation of concrete, and, if the concrete is not resistant to freezing and thawing, detrimental effects can occur. Meantime, higher water penetration causes greater chloride ingress if the concrete is subjected to deicing salts (ACI Committee 224, 2000).

Exact quantification of permeability of cracked concrete is not viable because of varying crack widths. Through an extensive study on permeability of cracked concrete, Aldea et al., (1999) showed that cracks in concrete having a mean crack width of 0.007-inches considerably increased permeability of concrete compared to uncracked concrete. Furthermore, previous research (Yaman et al., 2001) on newly constructed bridge decks in Michigan showed greater differences in permeability values (Table 9).

6 EXPERIMENTS FOR DETERMINING SEALANT PROPERTIES

The parameters that influence sealant penetration into concrete are given in Table 12. In order to fully evaluate sealant penetration, gradient of the curve h^2 against t, α, is needed (Eq. 8).

In this research, only contact angle measurements are carried out. Also, specimen surface is inspected by an optical microscope and atomic force microscope (AFM) before and after sealant application.

Table 12. Required Parameters to Calculate Intrinsic Permeability

Sealant properties	Concrete Properties
Viscosity Surface tension Contact angle	Mean pore radius Porosity

In addition to the properties given in Table 12, molecular size of the penetrating sealant is an important parameter which also establishes whether it is a water repellent or a pore blocker. The molecular size also defines the range of pore diameters that can be treated with a particular sealant. For different types of silanes and siloxanes, respective molecular sizes should be determined.

6.1 MEASUREMENT OF VISCOSITY

The viscosity of a real fluid is a measure of its frictional resistance to the relative motion of the fluid molecules. Fluid viscosity can be measured by a rotational concentric-cylinder viscometer (Figure 17).

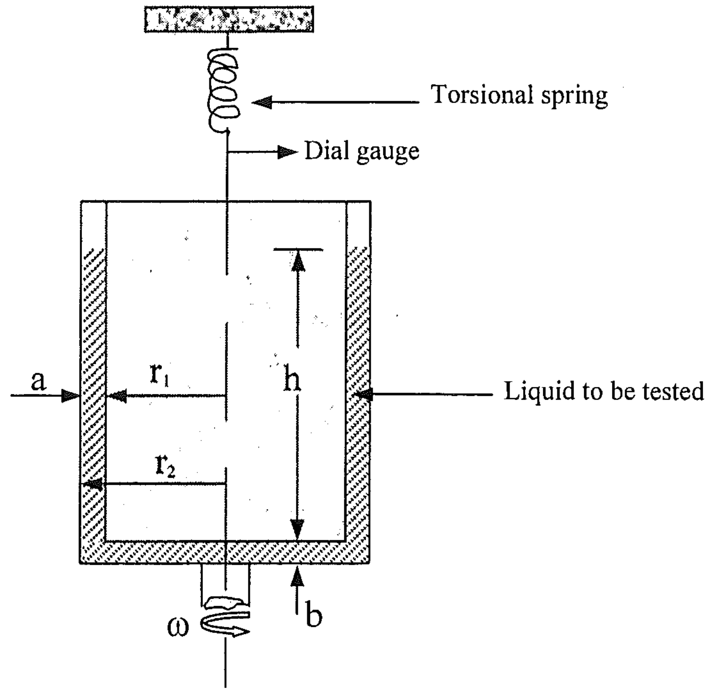


Figure 17. Schematic of a viscometer

The space between two cylinders is filled with the fluid whose viscosity (μ) is to be determined. The outer cylinder rotates at a constant angular velocity ω. The inner cylinder is stationary. The torque (T) transmitted by the enclosed fluid to the stationary cylinder is measured by the torsional strain of the restraining spring. The measured torque is due to shearing forces in the fluid between both the two concentric surfaces and two bottom surfaces (Pao, 1965).

The tangential velocity of the outer cylinder is given by $r_2\omega$

If the clearance is small, the rate of deformation is $\frac{dv}{dy} = \frac{r_2\omega}{a}$

The shearing stress developed in the fluid between the two cylindrical surfaces is

$$\zeta = \mu \frac{dv}{dy} = \mu \frac{r_2\omega}{a} \qquad (10)$$

The torque of the inner cylindrical surface is

$$T_l = r_l (A_l)\zeta = 2\pi r_l^2 h \mu \frac{r_2 \omega}{a} \quad (11)$$

For a small clearance b, torque at the bottom surface is

$$d\zeta_b = r\zeta\, dA = r\mu \frac{r\omega}{b} r dr d\theta \quad (12)$$

By integration, the torque at the bottom surface is

$$T_b = \frac{\mu \omega}{b} \int_0^{r_l} \int_0^{2\pi} r^3 dr\, d\theta = \frac{\mu \omega \pi r_l^4}{2b} \quad (13)$$

Total torque is the summation of top and bottom torques:

$$T = T_l + T_b = \frac{2\pi r_l^2 r_2 h \omega \mu}{a} + \frac{\pi r_l^4 \omega \mu}{2b} \quad (14)$$

By measuring the torque and other geometric parameters, dynamic viscosity of the liquid can be calculated from Eq. 15.

$$\mu = \frac{2abT}{\pi r_l^2 \omega (4 r_2 b h + r_l^2 a)} \quad (15)$$

Fluid viscosity is independent of variation in pressure but varies substantially with temperature.

Many types of viscometers are available on the market (Figure 18).

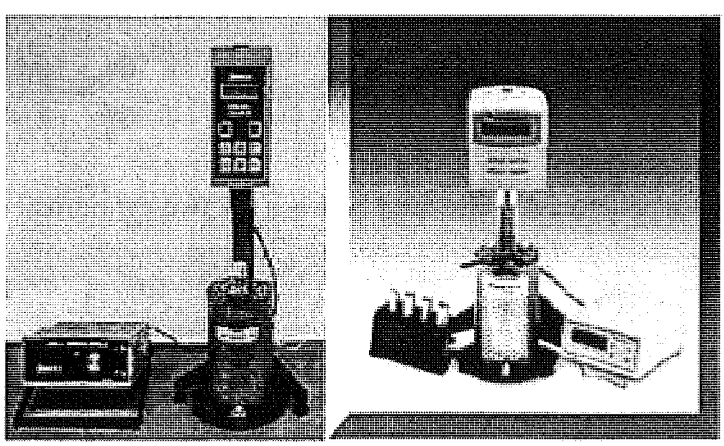


Figure 18. Rotational concentric-cylinder viscometer

6.2 CONTACT ANGLE & SURFACE TENSION

6.2.1 Contact Angle

A drop of water, or other liquid, in contact with one or several media always assumes the shape that gives the lowest total energy. If the surface is hydrophilic, it is favorable for the water to spread out over the surface. For the hydrophobic surface, the drop assumes a shape exposing a minimal area to the surface. The contact angle (θ) is measured by optical inspection and can be used to indicate the hydrophobicity of the surface (Figure 19). The phenomenon of wetting or non-wetting of a solid by a liquid is better understood by studying what is defined as the contact angle.

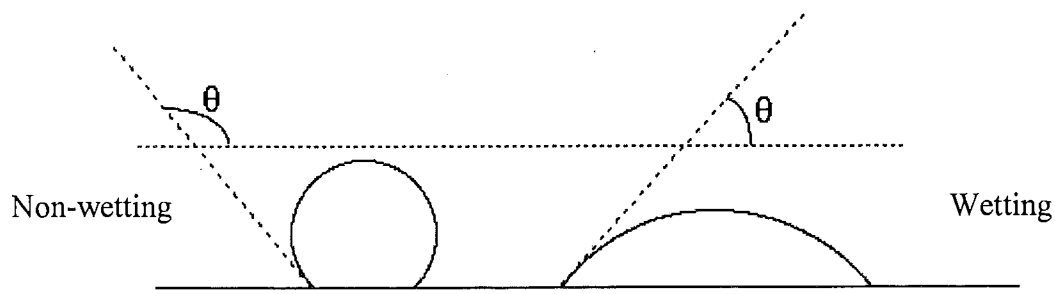


Figure 19. Contact angle for non-wetting and wetting liquids

Consider a droplet resting on a flat surface. The drop of liquid forming an angle may be considered as resting in equilibrium by balancing the three forces involved—namely, the interfacial tensions between solid and liquid (γ_{sl}), solid and vapor (γ_{sv}), and liquid and vapor (γ_{lv}). The angle between tangents to the solid-liquid and liquid-vapor interfacial, which is measured through the liquid, is known as the contact angle or wetting angle. The surface tension of the solid will favor spreading of the liquid, but this is opposed by the solid-liquid interfacial tension and the vector of the surface tension of the liquid in the plane of the solid surface. A smaller contact angle is preferred for greater depth of penetration. Therefore, the most important consideration for our purpose is the contact angle between concrete substrate and penetrating sealants and the critical surface-tension values.

Table 13 shows the contact angle values measured on the concrete surface before and after sealant application.

Table 13. Contact Angle Measurements (Deg)

Water/Cement	Silane/Cement	Water/Treated surface (silane)
49.5	Spreading	77

The level of increase in contact angle is proportional to the increase in surface hydrophobicity due to the silane application. Meantime, it was observed that the water droplet size decreased with time, indicating that water was penetrating into the concrete specimen. This is because silane penetrating sealant is a water repellent and not a pore blocker.

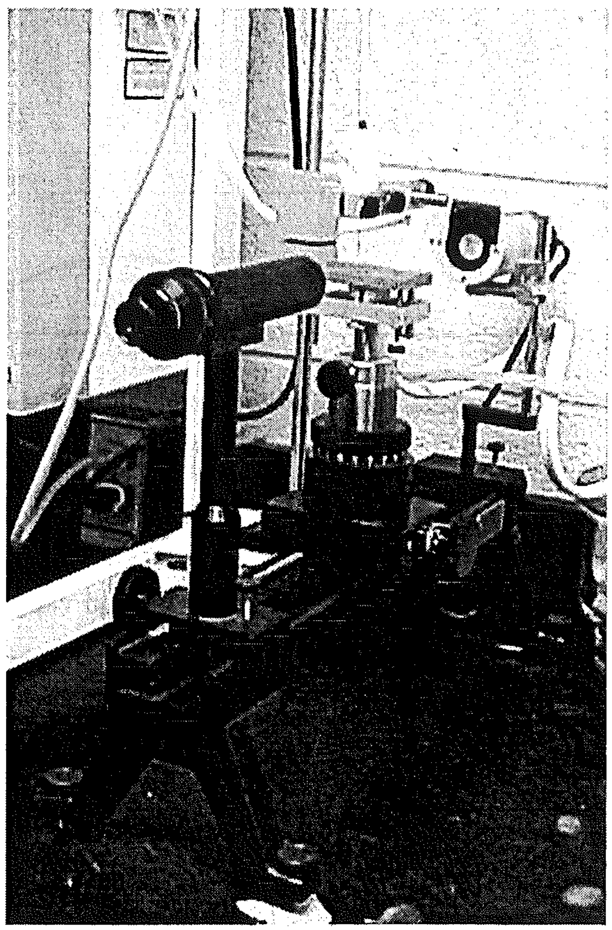


Figure 20. Apparatus for contact-angle measurements

6.2.2 Surface Tension

Surface tension is the energy required to expand the surface area of a liquid by a unit amount. Surface tension is important in understanding the wetting of materials and adhesion properties. The equation governing the relationship between contact angle and surface tension is the Young's equation.

$$\gamma_{sv} - \gamma_{sl} = \gamma_{lv} \text{Cos}\theta \qquad (16)$$

For the formulation given in Section: 5.1.1, interfacial tension between liquid and vapor (γ_{lv}) is required. The value of γ_{lv} can be determined from a simple experiment. The capillary force driving a liquid into a pore is a function of the surface tension of the liquid-gas interface, contact angle, and size of the pore. The driving force for the capillary action can be expressed as follows:

$$\text{Force} = 2\pi r\, \gamma_{lv} \text{Cos}\theta \qquad (17)$$

The gravitational pull acting on the liquid can be working in co-operation with or against the capillary force. When the gravitational pull is working against the capillary rise, the strength of the force is given by the following equation:

$$\text{Force} = \pi r^2 h \rho g \qquad (18)$$

Where ρ is the density of the liquid and h is defined in Figure 21.

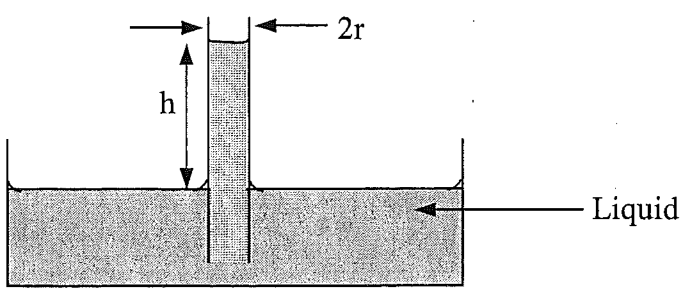


Figure 21. Rise of a liquid column due to surface tension

From Eq.17 and Eq.18,

$$\gamma_{lv} = rh\rho g/2\cos\theta \qquad (19)$$

From Eq.19 the value of γ_{lv} can be determined.

6.3 SPECIMEN SURFACE TOPOLOGY

Microscopic inspection of the concrete surface may be used as a quality control. Information in this section is provided for documentation purposes.

6.3.1 Atomic Force Microscope

The atomic force microscope (AFM) consists of an extremely sharp tip mounted on or integrated into the end of a tiny cantilever spring that is moved by a mechanical scanner over the surface to be observed. Every variation of surface height triggers the changes of the force acting on the tip. Changing forces cause bending moments of the cantilever that are measured by an integrated stress sensor at the base of the cantilever spring. The measured stresses are recorded for each line, which allows the reconstruction of the surface topology of the sample (Figure 22).

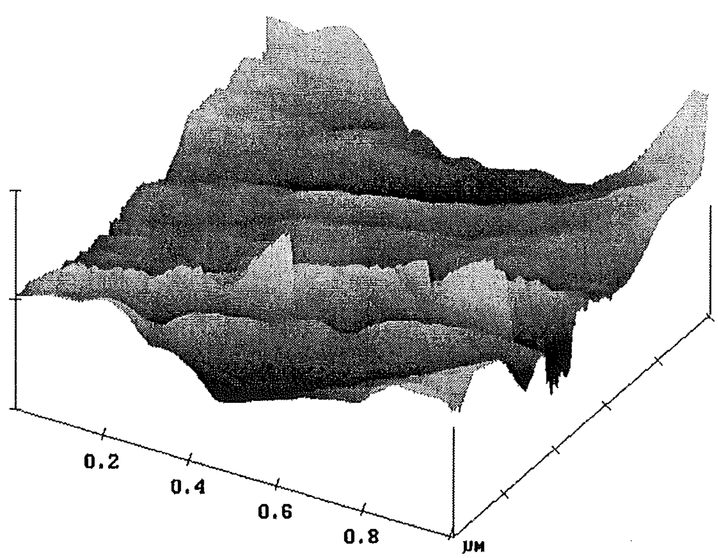
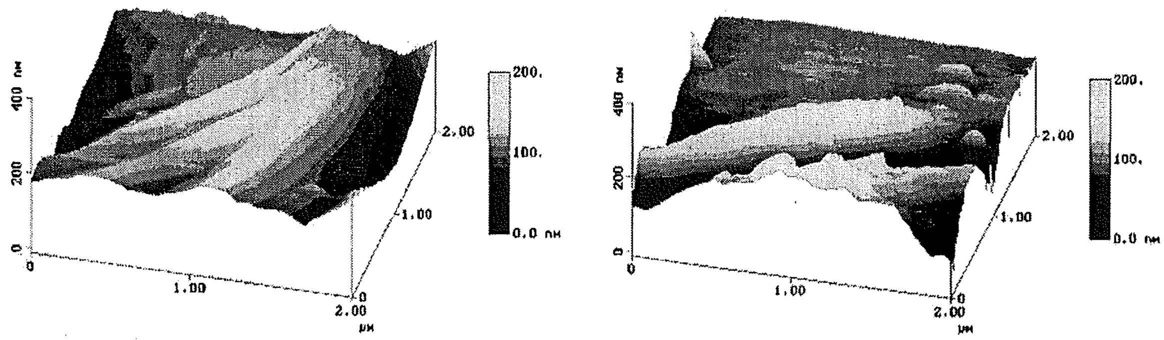


Figure 22. Surface topology of a concrete specimen

A surface image of the concrete specimen is generated before and after the penetrating sealant application (Figure 23). Since a picture is taken over a very small area (in nanometer scale), it is difficult to identify the exact location on the specimen in order to compare the images.



(a) (b)

Figure 23. Concrete surface (a) before and (b) after sealant application

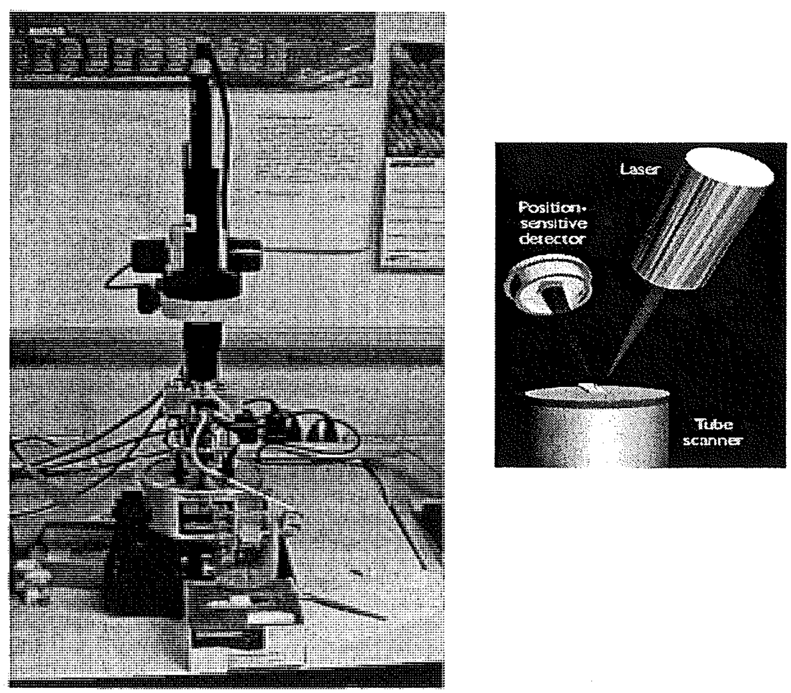


Figure 24. Atomic force microscope

6.3.2 Optical Microscope

Two locations on the specimen surface were inspected using an optical microscope. At the inspected location, cement paste on the surface of the specimen appeared as a white film (Figure 26 and Figure 27). The specimen was further inspected upon the application of the penetrating silane sealant (Figure 28). The differences between the appearance of the surfaces before and after the application of sealants were not detectable. The similarity of the surface appearance may be due to the fact that silane may have fully penetrated into concrete. But, for better understanding, additional experiments are needed.

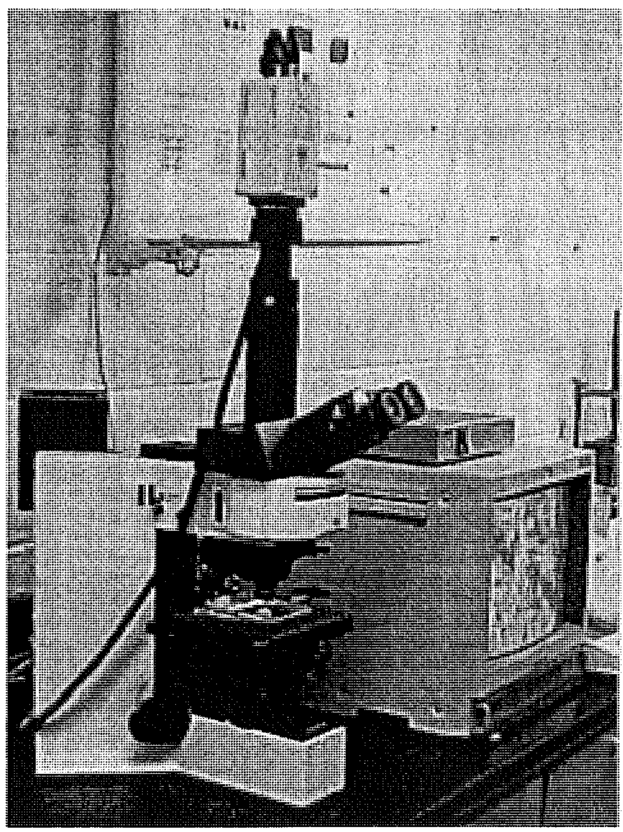


Figure 25. Optical microscope

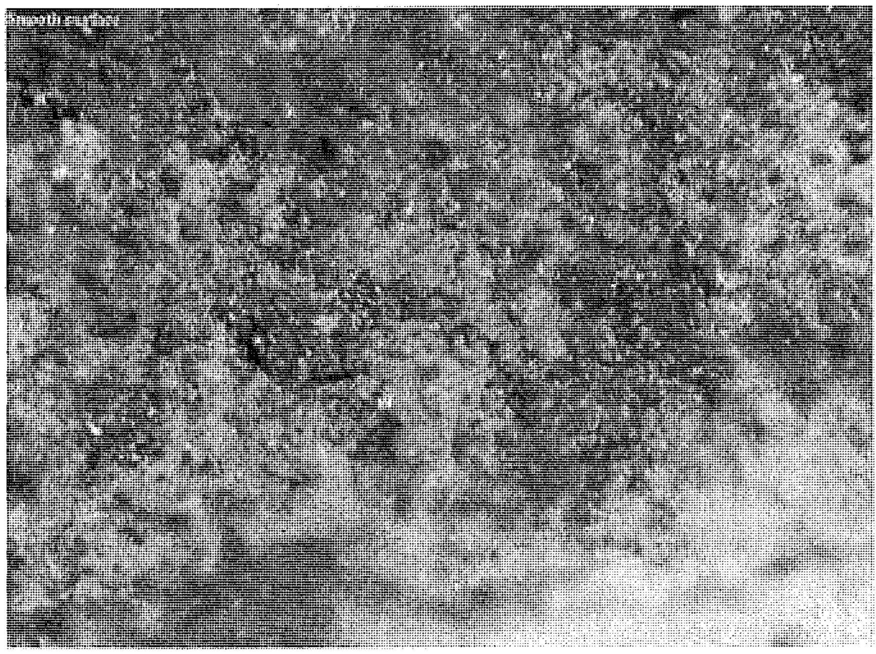


Figure 26. Concrete surface before sealant application (location 1)

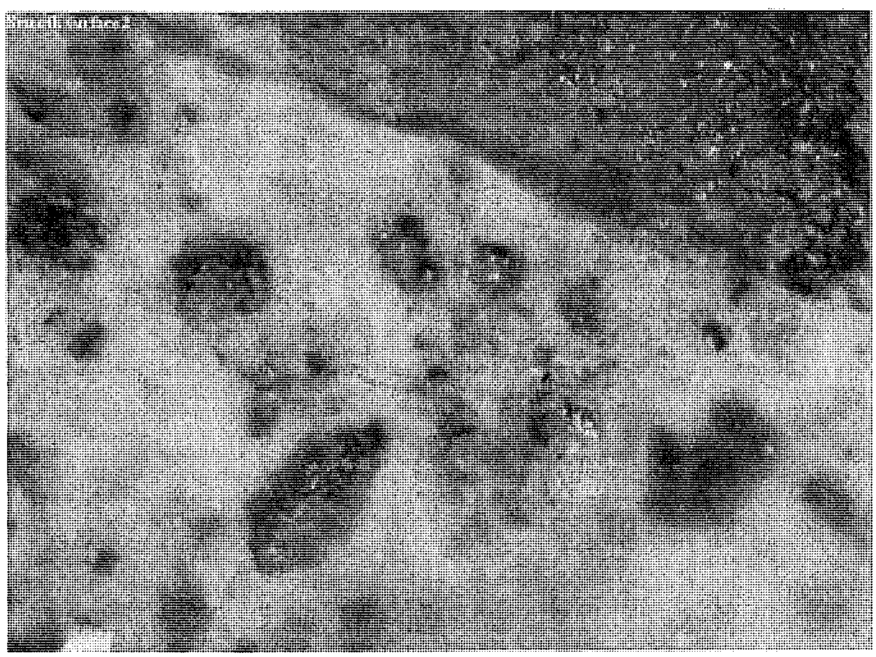


Figure 27. Concrete surface before sealant application (location 2)

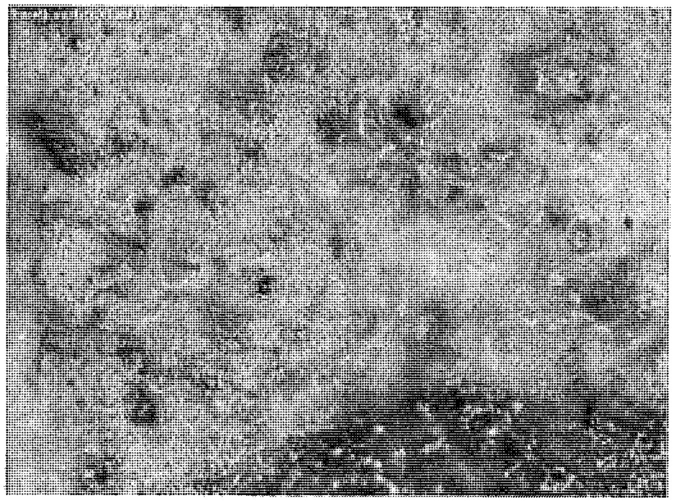


Figure 28. Concrete surface after sealant application

7 PROPOSED SELECTION AND EVALUATION CRITERIA

7.1 SELECTION OF A SURFACE TREATMENT

Many of the factors pertaining to the sealant as well as the concrete surface need to be considered while selecting a suitable penetrating sealant. These factors are summarized in Table 14. Considering the factors given in Table 14 and the available test methods, a flow chart (Figure 29) was developed for the penetrating sealant's selection. Additionally, based on the considerations given in Table 14, we reproduced a flowchart (Figure 30), developed by Basheer et al., (1997) to help in the condition assessment of concrete bridge decks and the selection process of penetrating sealants.

According to literature, some sealants can provide the required levels of performance in protecting concrete from chloride intrusion and water permeation but may not be suitable when their durability is considered. Therefore, it is necessary to understand the relationship between the performance and durability of penetrating sealants for the effective use of the flowcharts given in Figure 29 and Figure 30 (Basheer et al., 1997).

Table 14. Factors to be Considered in Selection of Penetrating Sealants

Feature	Consideration
Original Substrate	New construction or remedial work Condition of the deck Prior surface treatments Surface contamination
Environment	Atmospheric, marine, etc. Presence of moisture Presence of pollutants
Sealant durability	Penetration depth Ultraviolet resistance Reactivity with hydrated cement paste Weathering Alkali resistance
Protection of concrete	Chloride absorption Water absorption Water-vapor transmission Deicer scaling resistance
Service	Skid resistance
Application features	Surface preparation requirements Brushing, spraying characteristics Tolerance to substrate moisture Temperature dependence Site access and lane closure time
Life-cycle cost	Unit material cost Number of applications Labor cost Maintenance cost

Source: Cady, 1994, and Basheer et al., 1997

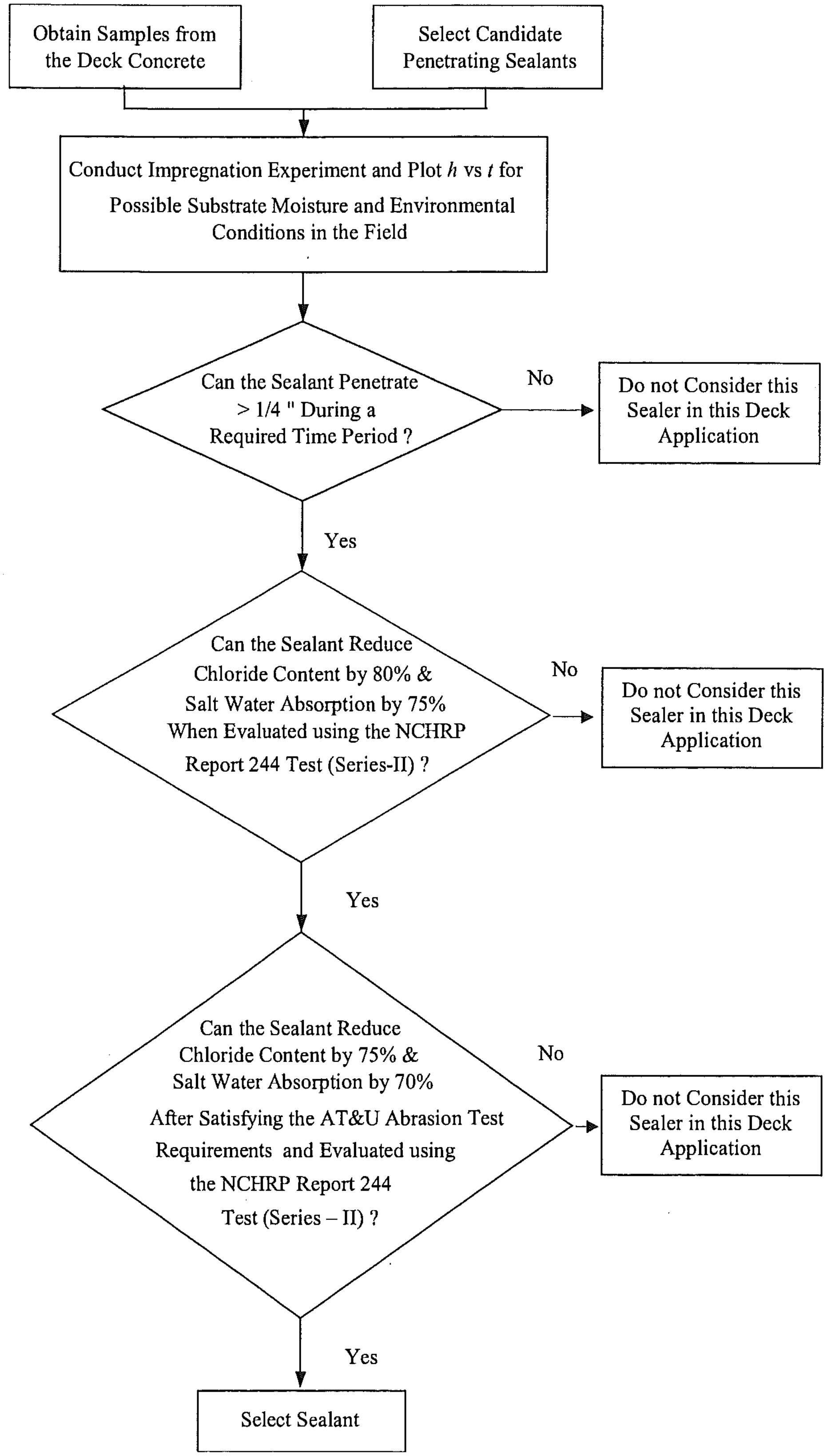


Figure 29. Penetrating sealant selection procedure flowchart

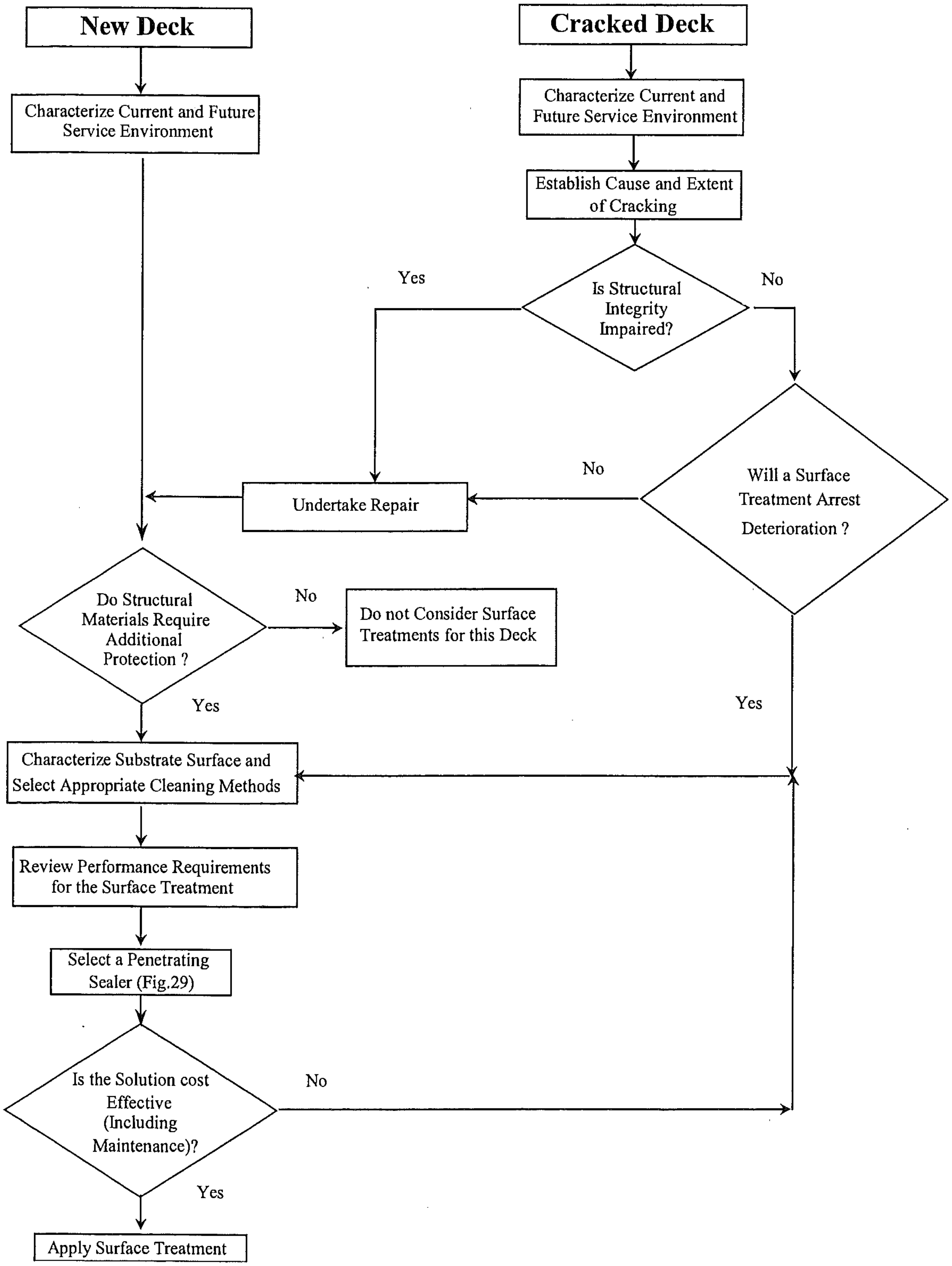


Figure 30. Condition assessment and surface treatment procedure flowchart

7.2 ENVIRONMENTAL ASPECTS

Volatile organic compounds (VOC) that are contained in sealants are an environmental concern. In the presence of sunlight VOC reacts with nitrogen oxides to form smog. The Clean Air Act, passed by the U. S. Congress in 1990, refers to VOC's and mandates lower limits. Several State Highway Agencies have also established limitations for VOC's in waterproofing sealers. For example, Phoenix, Los Angeles, San Diego, and San Francisco limit the VOC's to 3.33 lb/gal (400 grams per liter), and New Jersey and New York City to 5.00 lb/gal (600 grams per liter) (Cady, 1994).

7.3 EVALUATION & TESTING

Selecting a penetrating sealant that meets the requirements relative to a specific application is vital to achieve the expected performance. During the different stages of the sealant selection process, one must carry out several tests. Cady (1994) specified that product testing and evaluation requires four stages: (1) product qualification, (2) product quality assurance, (3) field application quality assurance, and (4) field testing for assessment of sealer reapplication frequency and performance.

Product qualification testing is intended to identify the products that meet the requirements relative to specific applications. Product quality assurance tests also detect quality degradation during storage. During and after application of the sealant, several tests are needed to ensure that the sealant has been properly applied on carefully prepared concrete substrates, to assess sealer reapplication needs, and to judge sealer performance.

At this time, when selecting penetrating sealants, most of the State Highway Agencies use the testing methods described in NCHRP Report 244 (Series - II) (Appendix A). In these tests, there is no special requirement for the moisture conditions in the concrete substrate at the time of sealant application. These tests are applicable for the first three stages: product qualification, product quality assurance, and field application quality assurance.

A test procedure called "Water Proofing After Surface Abrasion," recommended by AT&U (Appendix B) for penetrating sealers for use on traffic surfaces, is the most widely used testing method for evaluating the effectiveness of the sealant. This is a well-accepted method by researches for determining the working or effective depth of penetration (Bush, 1998; McGettigan, 1992).

There is no well-accepted testing method to evaluate the field performance of the sealer. Some researchers explored the electrical resistivity method or modified versions of it to quantify the efficacy of the treated surface. There are also several experimental methods for determining the depth of penetration in the laboratory—mainly the splitting test and neutron radiography techniques.

We propose a new test procedure for evaluating the field performance: when casting the bridge deck, prepare and keep two 24" x 24" x 4" specimens under similar environmental and curing conditions. While applying the sealant treatment to the bridge deck, follow the same procedure (cleaning, application, and curing) on one of the specimens. Keep the other specimen for reference measurements. After one week of sealant application, use the electrical resistivity method to evaluate the relative performance of the treated specimen and the deck. We endorse the resistivity measurement procedure recommended by Cady (1993), with modifications (Appendix C): instead of the original procedure's 2-pin (probe) mode, we advocate a 4-pin mode of the resistance meter. This is because the measurement that is obtained through 4-pin mode is independent of the resistance of the four pins and cables from the connections to the pins. Thus the measurement procedure only requires application of four stripes of conductive paints with 1/8-inch spacing between each strip. For satisfactory results, the resistivity test results between the sealed specimen and the deck should be identical. The resistivity measurements represent an average resistivity of concrete to a depth equal to the pin or probe spacing. If the results are satisfactory, take cores from the specimen and use them to document the depth of penetration, using either the splitting test method or the neutron radiography method. Additional samples can be used to find the effective depth of penetration using the test method recommended by AT&U.

For new decks, after approximately six months of silane or siloxane application, cracking of the concrete deck should be appraised. If the crack widths are less than 0.002-inches, silane sealers can be used further. If the crack widths are in general less than 0.08-inches, HMWM in conjunction with silane sealers can be used. Use of HMWM on crack widths greater than 0.08-inches is not effective; these cracks should be repaired according to ACI Manual of Concrete Practice (ACI Committee 224, ACI 244.1R-93).

Previously untreated cracked bridge decks that are older than one year can be sealed using the same procedure as described above, provided that adequate surface cleaning and preparation methods are employed.

7.4 SURFACE PREPARATION & APPLICATION PROCEDURES

Deck concrete must be at least 28 days old for sealant application. The bridge deck must be cleaned thoroughly before the application of the penetrating sealant. High pressure water blasting can be used to clean the curing compounds on the newly constructed bridge decks. While selecting the curing compounds, consider sealant application, giving preference to removable compounds. For bridge decks that are more than one year old, the recommended cleaning method is dustless abrasive shot blasting. Since most likely the bridge is already opened to traffic, be sure to remove oil, grease, rubber, other organic contaminants, and the carbonated layer on the deck.

The cleaned surface of the bridge deck needs to dry for a certain period. Generally, a 2-day drying period is recommended, depending on the prevailing environment conditions. In principle, the drier the surface, the better the penetration depth. There are several application methods for the penetrating sealants, the most preferred being surface flooding, followed by air-less spray and roller. At least two coats of sealant application are recommended on the cleaned surface. The minimum drying period between applications, depending on the prevailing environmental conditions, is approximately four hours. Manufacturers' recommendations should be taken into account during each tier.

8 CONCLUSIONS & RECOMMENDATIONS

8.1 CONCLUSIONS

The primary conclusions generated in this research are related to sealant effectiveness for improving bridge deck durability. There are silane products currently available that can be used for waterproofing bridge decks and can penetrate to reasonable depths into deck concrete. However, successful applications of the sealants require extreme attention to detail, such as deck cleaning, crack sealing, and repetition of this process in regular preventive maintenance cycles. Additionally, the application procedures will require careful and accurate implementations of QC/QA procedures to observe their improvement in the long term.

The primary conclusions are as follows:

1. Water repellents can form an effective water repellent surface on bridge decks without inhibiting the breathability of concrete.

2. Sealant penetration into concrete can be controlled by proper selection of sealant for that specific concrete.

3. Concrete with sealant may exhibit uniform durability along the surface.

4. Sealants can be used in conjunction with high molecular weight methacrylate on cracked concrete.

5. Existing concrete surfaces should be thoroughly clean and reasonably dry before application of the sealants.

6. The level of moisture in the concrete that is necessary for sealant reaction while allowing required depth of penetration is not known.

7. Sealants applied via the consecutive flooding approach provide additional penetration into moist concrete surfaces.

8.2 RECOMMENDATIONS

The use of sealants for bridge deck protection is a maintenance policy decision. The current approach to unprotected bridge deck concrete may need to be revised considering today's operational constraints.

This study does not endorse the use of sealants for bridge deck protection prior to reviewing controlled field implementations as well as the development and testing of QC/QA procedures. However, this study does conclude that sealants can provide effective deck protection if used either once for decks placed in the fall or at regular maintenance cycles. It is very obvious that the repeated use protocols may have a low benefit/cost when operational costs are considered.

The following recommendations are provided if the sealant use is adopted for deck protection:

1. Minimum sealant penetration depth of 0.25-inch is required to provide effective sealing layer for concrete bridge deck.
2. Neat silane can provide the required durability for bridge decks.
3. A single sealing cycle is sufficient for late construction if regular preventive maintenance cycles are not required. Otherwise, four- to five-year sealing cycles are required.
4. Moisture is needed for sealant reaction. But it inhibits the sealant penetration. Therefore, the deck surface at least should be dry when the sealant is applied.
5. Deck cracks should be sealed. If the maximum crack width is less than 0.002-inches, silane sealers are adequate to seal the deck. When the crack width is less than 0.08-inches, silane and HMWM sealers can be applied provided adequate drying period is maintained between silane and HMWM applications.

9 RECOMMENDATIONS FOR FURTHER RESEARCH

The research proposed is in two directions:

1. Sealant properties:
    - Evaluation of evaporation of penetrating sealants when flooding the concrete bridge deck under different environmental conditions.
    - Quantification of sealant life-cycle performance.
2. Performance tests for field applications:
    - Verification of resistivity test, which uses the linear-array technique as a quality control test for field applications.
    - Development and verification of a field-test procedure for sealant performance evaluation.

10 REFERENCES

ACI Committee 224, ACI 244.1R-93., (2001). "Causes, Evaluation and Repair of Cracks in Concrete Structures." ACI Manual of Concrete Practice, American Concrete Institute, Detroit, Michigan.

ACI Committee 224, ACI 244R-90., (2000). "Control of Cracking in Concrete Structures." ACI Manual of Concrete Practice, American Concrete Institute, Detroit, Michigan.

Aldea, C. M., Shah, S.P., and Karr, A., (1999). " Effect of Cracking on Water and Chloride Permeability of Concrete." *Journal of Materials in Civil Engineering,* Vol. 11, No. 3, pp. 181-187.

Al-Qadi, I. L., Weyers, R.E., and Dutta, T., (1994). "Optimization of Concrete Drying Temperature for Monomer Impregnation." *Journal of Materials in Civil Engineering,* Vol. 6, Issue 1, pp. 54-64.

Basheer, P. A. M., Basheer, L., Cleland, D. J., and Long, A. E., (1997). "Surface treatments for concrete: assessment methods and reported performance." *Construction and Building Materials,* Vol. 11, Issues 7-8, pp. 413-429.

Basheer, P. A. M., McCauley, A., and Long, A. E., (1997). "Influence of Moisture Condition of Concrete on the Performance of Surface Treatments." *Special Publication 170 (SP - 170),* American Concrete Institute.

Bush, T., (1998). "Laboratory Test Procedures for Evaluating Concrete Treated with Sealers." *ACI Material Journal*, V. 95, No. 4, pp. 436-444.

Bush, T., Kamel, A., and Kalluri, P., (1997). "Influence of Field Variables on Laboratory Performance of Silane Treated Concrete." *ACI Material Journal*, V. 94, No. 3, pp. 193-202.

Cady, P.D., (1994). "Sealers for Portland cement concrete highway facilities." NCHRP Synthesis 209, Transportation Research Board, National Research Council, Washington, D.C.

Cady, P. D., (1993). *Condition Evaluation of Concrete Bridges Relative to Reinforcement Corrosion, Vol. 8, Procedure Manual*, SHRP-S-330, Strategic Highway Research Program, National Research Council, Washington, DC.

Carter, P. D., (1994). "Evaluation of Dampproofing Performance and Effective Penetration Depth of Silane Sealers in Concrete." *Special Publication 151 (SP - 151)*, American Concrete Institute.

Delucchi, M., Barbucci, A., and Cerisola, G., (1997). "Study of the physico-chemical properties of organic coatings for concrete degradation control." *Construction and Building Materials,* Vol. 11, Issues 7-8, pp. 365-371.

Dry, C. M., (2000). "Three designs for the internal release of sealants, adhesives, and waterproofing chemicals into concrete to reduce permeability." *Cement and Concrete Research,* Vol. 30, Issue 12, pp. 1969-1977.

German Federal Highway Research Institute., (2002). Rainer WRUCK, Bundesanstalt für Straßenwesen, German Federal Highway Research Institute, Brüderstraße 53, 51427 Bergisch Gladbach, Germany.

Jones, M. R, Dhir, R. K., and Gill, J P., (1995). " Concrete Surface Treatment: Effect of Exposure Temperature on Chloride Diffusion Resistance." *Cement and Concrete Research*, Vol.25, No.1, pp.197-208.

Kagi, D. A. and Ren, K. B. (1995). " Reduction of Water Absorption in Silicate Treated Concrete By Post-Treatment With Cationic Surfactants."*Building and Environment*, Vol.30, No.2, pp. 237-243

Koichi, M., Rajesh, C., and Toshiharu, K., (1999). *Modeling of Concrete Performance Hydration, Microstructure Formation and Mass Transport*. Routledge, New York.

Kompen, R., Senior Advisor, Road Research Laboratory, Norwegian Public Roads Administration. E-mail: reidar.kompen@vegvesen.no (Personal contacts, 2002).

Krauss, P. D., and Rogalla, E. A., (1996). "Transverse Cracking in Newly Constructed Bridge Decks." NCHRP Report 380, Transportation Research Board, National Research Council, Washington, D.C.

Lai, David., Acting Manager, Bridge Office, Ministry of Transportation, Ontario. E-mail: David.Lai@mto.gov.on.ca (Personal contacts, 2002).

LaRosa Thompson, J., Silsbee, M.R., Gill, P.M., and Scheetz, B.E., (1997) "Characterization of Silicate Sealers On Concrete." *Cement and Concrete Research*, Vol. 27, No. 10, pp. 1561-1567

Lee, L. H., (1987). "Adhesives and sealants for severe environments." *International Journal of Adhesion and Adhesives*, Vol. 7, Issue 2, pp. 81-91.

Lester, P., Chief Bridge Engineer, Highway Design Division, Government of Newfoundland and Labrador Department of Works, Services and Transportation. http://www.gov.nf.ca (Personal contacts, 2002).

Liberatore, F. R., Manager of Bridge Operations, Connecticut Department of Transportation E-mail: Franco.Liberatore@po.state.ct.us (Personal contacts, 2002).

Lynch, L., Steffes, R., Chehovits, J., Voigt, G., Evans, L. E., and Al-Qadi, I. L. (1993). "Joint- and Crack-Sealing Challenges." A3C13: Committee on Sealants and Fillers for Joints and Cracks, SHRP-H-349. Transportation Research Board, National Research Council, Washington, DC.

MacGillivray, I., Director, Research Management Division, Iowa Department of Transportation. E-mail: Ian.MacGillivray@dot.state.ia.us (Personal contacts, 2002).

Mark, V. J., (1987). "High Molecular Weight Methacrylate Sealing of a Bridge Deck." Transportation research record 1204. Iowa Department of Transportation.

Mays, G. C., (2001). "Performance requirements for structural adhesives in relation to concrete strengthening." *International Journal of Adhesion & Adhesives,* Vol. 21, pp. 423–429

McCarter, W. J., (1998). "Surface-treated slag concrete: Assessing performance under cyclic wetting." *Journal of Materials in Civil Engineering,* Vol. 10, Issue 3, pp. 198-201.

McCarter, W. J., (1996). "Assessing the Protective Qualities of Treated and Untreated Concrete Surfaces under Cyclic Wetting and Drying." *Building and Environment,* Vol. 31, Issue 6, pp. 551-556.

McDonald, N. L., Bridge Engineer, Iowa Department of Transportation. (Personal contacts, 2002).

McGettigan, E., (1992). "Silicon-Based Weatherproofing Materials." *Concrete International*, Vol. 14, No. 6, pp. 52-56.

McGettigan, E., (1990). "Application Mechanism of Silane Weatherproofers." *Concrete International*, Vol. 12, No. 10, pp. 66-68.

McMullen, M. Colorado Department of Transportation. http://www.dot.state.co.us. E-mail: Michael.McMullen@dot.state.co.us (Personal contacts, 2002).

Mehta, P. K., and Monteiro, P. J. M., (1993). *Concrete: Structure, Properties, and Materials.* Second Edition, Prentice Hall, New Jersey.

Michael, J. L., Chairman, Bridge Deck Protection Committee, California Department of Transportation. E-mail: Michael_J_Lee@dot.ca.gov (Personal contacts, 2002).

Miller, T. D., Engineering Technician, Materials Research Group, Construction and Technology Division, Michigan Department of Transportation. E-mail: millerth@mdot.state.mi.us. (Personal contacts, 2001).

Neville, A. M., (1995). *Properties of Concrete*, Fourth Edition, Longman Group Limited, England.

Neville, A. M. and Brooks, J. J., (1987). *Concrete Technology*, First Edition, John Wiley & Sons, Inc., New York.

Nolan, E., Basheer, P. A. M., and Long, A. E., (1995). "Effects of three durability enhancing products on some physical properties of near surface concrete." *Construction and Building Materials,* Vol. 9, Issue 5, pp. 267-272.

Pao, R. H. F., (1965). *Fluid Mechanics*, Second Edition, John Wiley and Sons, Inc., New York.

Pappas, J., Chief Material and Research Engineer, Delaware Department of Transportation E-mail: Jpappas@mail.dot.state.de.us (Personal contacts, 2002).

Perenchio, W. F., (1988). "Durability of Concrete Treated with Silanes." *Concrete International*, Vol. 10, No. 11, pp. 34-40.

Pfeifer, D. W., and Scali, M. J., (1981). "Concrete sealers for protection of bridge structures." NCHRP report 244, Transportation Research Board, National Research Council, Washington, D.C.

Polder, R.B., (1997). Ministry of Transport Civil Engineering Division, Utrecht, The Netherlands, *Construction and building Materials*, Vol.11, No.4, pp 259-265.

Powers, T. C., (1968). *The Properties of Fresh Concrete*. John Wiley & Sons, Inc., New York.

Ramachandran, V. S., Feldman, R. F., and Beaudoin, J. J., (1981). *Concrete Science,* Heyden & Son Ltd., Philadelphia.

Reynes, J., Woignier, T., and Phalippou, J., (2001). "Permeability measurements in composite aerogels: application to nuclear waste storage." *Journal of Non-Crystalline Solids* 285, pp. 323-327.

Rogers, A. D., Lee-Sullivan, P., and Bremner, T. W., (1999). "Selecting concrete pavement joint sealants I: Proposed test protocol." *Journal of Materials in Civil Engineering*, Vol. 11, Issue 4, pp. 302-316.

Strang, F., New Brunswick Department of Transportation. E-mail: Fred.Strang@gnb.ca (Personal contacts, 2002).

Udegbunam, O., Yaman, I. O., Aktan, H., and Hohm, T., (1999) "Developing a Rapid Measure of Concrete Permeability for use in QA/QC Specifications," *Transportation Research Board*, Paper No: 990565, January.

Whiting, D., Ost, B., Nagi, M., and Cady, P. D., (1992). *Condition Evaluation of Concrete Bridges Relative to Reinforcement Corrosion*, Vol. 5, Methods for Evaluating the Effectiveness of Penetrating Sealers, SHRP-S/FR-92-107, Strategic Highway Research Program, National Research Council, Washington, DC.

Wiss, Janney, Elstner Associates, Inc., (1999). *Cracking Repair Trials, City Island Bridge at US 61 and 151 over the Mississippi River for Iowa Department of Transportation*. WJE No. 971345.

Wittmann, F. H., Gerdes, A., Wegner, M., and Sadouki, H., (1998). *Water Repellent Treatments of Building Materials*, Aedificatio Verlag, Freiburg I.B.

Wong, J., Technical Standard Branch, Alberta Department of Transportation. E-mail: Jim.Wong@gov.ab.ca (Personal contacts, 2002).

Yaman, O., Karaca, H., and Aktan, H., (2001). *Evaluation of Concrete Permeability by UltrasonicTesting Techniques*, Phase IV Final report, Wayne State University, Detroit, MI.

10.1 REFERENCE WEBSITES

1. http://www.transportation.org/aashto/home.nsf/FrontPage (ASSHTO Website)
2. http://www.tamms.com/toc2.html (TAMMS Industries)
3. http://www.seal-it.sk.ca/masonry.htm (Seal-it)
4. http://www.ifm.liu.se/~hanka/methods/contact.shtml (Contact angle measurements)

5. http://surfactants.net/contactanglestandards.htm#ca (Contact angle measurements)
6. http://stm2.nrl.navy.mil/how-afm/how-afm.html# (AFM general concept)
7. http://hyperphysics.phy-astr.gsu.edu/hbase/surten.html (Surface tension of water)
8. http://www.nilssoneleclab.com/ (Nilsson Electrical Laboratory, Inc)
9. http://www.acdlabs.com/ (Advanced Chemistry Development Inc)

10.2 SEARCH ENGINES

1. http://www.google.com
2. http://www.scirus.com
3. http://www.sciencedirect.com

APPENDIX A

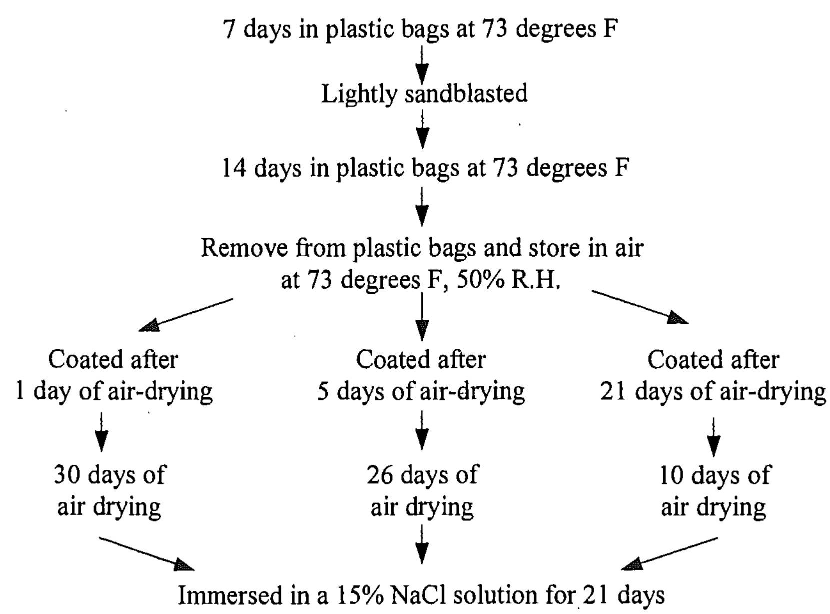
NCHRP Report 244 (Series - II) Test Procedure

The testing procedures described in this section are extracted from *Concrete sealers for protection of bridge structures*, NCHRP Report 244, Transportation Research Board, National Research Council, Washington, D.C.

A.1 Test Procedure

After stripping at age 1 day, specimens are placed within sealed heavy duty plastic bags for moist curing in the controlled climate room. At age 7 days, the specimens are lightly sandblasted, labeled, and weighted to the nearest 0.1-gram. Immediately after this initial weighing, the specimens are returned to the plastic bags and placed in the controlled climate room for 14 more days of moist curing. At age 21 days, the specimens are removed from the plastic bags and stored in the controlled room on steel racks for air-drying. They should be moved periodically to reduce the effects of variations in air circulation.

The penetrating sealants are applied to some specimens after they are dried for one day, to others after they are dried for five days, and to others after they are dried for 21 days. After coating, the specimens are returned to the controlled climate room for continued air-drying. During air-drying (before and after coating), the cubes are weighted to the nearest 0.1-gram at intervals of approximately 7 days. At an age of 54 days, all specimens are then immersed in a 15-percent NaCl solution. This procedure is illustrated in the following diagram.



This test procedure includes two types of uncoated control specimens. One pair remains in the controlled-climate room during the entire test period. Their weight losses are periodically monitored. The other pair of control specimens is subjected to the air-drying and saltwater soaking tests in the same manner as the coated specimens.

All the specimens are immersed in a 15-percent NaCl water solution for 21 days. During this soaking period, the gain in weight at 3, 6, 9, 12, 15, 18, and 21 days is determined to the nearest 0.1-gram. After the 21-day saturated-surface-dry (SSD) wet weight is determined, the specimens are returned to the air in the controlled-climate room so weight-loss or water-vapor-transmission characteristics can be observed. During this 21-day final air-drying period, the loss in weight at 3, 6, 9, 12, 15, 18, and 21 days is determined to the nearest 0.1-gram. After the final 21-day air-drying period, each cube is mechanically split in half. One half is crushed, and the total chloride-ion content of the crushed concrete is determined using an acid-digestion, potentiometric titration procedure.

Water absorption is calculated as percentage of weight gain during the soaking period.

$$\text{Weight gain} = \frac{\text{Weight gain (Treated specimen)}}{\text{Weight gain (Untreated specimen)}} \times 100\ \%$$

Water-vapor transmission is calculated by comparing the weight gain during soaking and the weight loss during air-drying.

$$\text{Water vapor transmission} = \frac{\text{Weight loss}}{\text{Weight gain}} \times 100\ \%$$

Total chloride-ion content of the test specimens prepared for NCHRP Report 244 (Series-II) tests was determined by using the acid-digestion potentiometric titration procedure. Erlin Hime Associates conducted this test.

APPENDIX B

Testing Procedures Recommended by Alberta Transportation and Utilities

The definitions and the testing procedures given in this section are extracted from the standards published by Alberta Infrastructure, Technical Branch. These publications are:

- Test Procedures for Measuring the Vapor Transmission, Waterproofing, and Hiding Power of Concrete Sealers (BT 001 – July 00).
- Best Practice Guidelines for Selecting Concrete Bridge Deck Sealers.

B.1 Alberta Infrastructure's Sealer Classification:

There are three types of sealers on the Alberta Infrastructure approval list, and each type of sealer has a specific application and use.

N.B: Only classifications of Type 1 (penetrating) sealers are discussed in Appendix B.

Type 1 Sealer, Penetrating

- <u>Type 1a</u>

  Penetrating silane sealers used in sheltered areas and where the relative humidity of the concrete is less than 55 percent. The typical solids-content range for Type 1a sealer is 14 percent to 32 percent. These sealers are applied on concrete surfaces that are 28 days or older.

- <u>Type 1b</u>

  Penetrating silane sealers used in traffic-bearing areas for outdoor use. The relative humidity of the concrete is 75 percent or less. The application rate is usually higher than the Type 1a for the same brand of sealer. These sealers are generally called 40-percent silane sealer, which has a solids content range of 25 percent to 33 percent. These sealers are used on concrete decks that are cured for 28 days or longer.

- <u>Type 1c</u>

  Penetrating sealer that is considered a 100-percent silane sealer. The solids content of this sealer ranges from 65 to 72 percent. The relative humidity of the concrete is 85 percent or less. This type of sealer is used on precast concrete that is steam cured for one to five days (28 days is preferable) before application.

B.2 Determination of Waterproofing Performance

Weigh both the sealed and control cubes immediately before immersing them in water, and record the weight. Then totally immerse the cubes in tap water (temperature 70 to 77 F, or 23 ± 2 C). Support the cubes so that all the surfaces are freely exposed to water, with the screeded faces upward and 1-inch (25-mm) below the water level. Remove the cubes from the water tank after 120 hours. Surface-dry the cubes to produce a saturated-surface-dry (SSD) condition and then re-weigh them within 60 seconds from the time you remove from the bath. Light toweling may be used to aid in surface drying. Report the average weight gained by each set of cubes during immersion. Waterproofing performance of sealed cube as a percentage of the control cube is to be calculated as follows:

$$\text{Water proofing performance} = \frac{CG - TG1}{CG} \times 100\ \%$$

CG – average weight gain per cube of the control set

TG1 – average weight gain per cube of the sealed set

B.3 Determination of Waterproofing Performance After Surface Abrasion on Type 1 Sealers

This test applies to sealers that are approved as Type 1 sealers used on bridge decks when exposed to abrasion. After performing the tests in B.2, oven dry the same set of sealed cubes at 140 ± 3.6 F (60 ± 2 C) until the moisture gained during the immersion in B.2 is removed within ± 1-gram. Weighing before and after drying is required for this adjustment.

Once the drying is completed, sandblast the entire surface of the cubes to evenly remove an average amount of cement paste from all sides of the treated cubes. Only one cube face will be exposed to sandblasting at any time. Mechanically shield the other faces from the sandblast spray. Maintain the nozzle at a_90 angle to the cube face being blasted. Sandblasting leaves a rough surface, making it difficult to measure the amount of surface removed. In order to improve the measurement of surface loss per cube side, weigh the material removed from each face. Remove mass from each of the six faces as follows:

Table B-1. Recommended Amount of Surface Loss After Sandblasting

Sealer Type	Weight Removed Per Face, g	Cumulative Loss Per Cube, g
1a	12.0 ± 1.0	72.0 ± 2.0
1b	12.0 ± 1.0	72.0 ± 2.0
1c	24.0 ± 1.0	144.0 ± 2.0

Weigh the sealed cubes after abrasion and record the weight. Immerse the cubes as in B.2 to determine the effect of surface abrasion on the waterproofing performance of the sealer.

Calculate the waterproofing performance after abrasion as follows:

$$\text{Waterproofing performance} = \frac{CG - TG2}{CG} \times 100\ \%$$

CG – average weight gain per cube of the control set as obtained in B.2.

TG2 – average weight gain per cube of the sealed set after abrasion.

APPENDIX C

Standard Test Method for Determining the Relative Effectiveness of Penetrating Concrete Sealers by an Electrical Resistance Method

The test procedure described below is extracted from SHRP Report (SHRP-S-330) *Condition Evaluation of Concrete Bridge Relative to Reinforcement Corrosion*, Volume: 8, Procedure Manual.

C.1 Scope

- This test method covers the determination of the changing electrical resistance between two stripes of conductive paint applied to a concrete surface. The test method can be used as an indication of the relative effectiveness of penetrating sealers applied to concrete but does not determine the actual resistivity of the concrete.
- The surface resistance measured by this test method is independent of the dimensions of the concrete, provided that at least 1-inch (25-mm) of clearance is allowed to the nearest edge of the concrete under test.
- The method is applicable to both laboratory specimens and field structures over a temperature range of 50° F (10° C) to 120° F (49° C).
- The values stated in inch-pound units (or cgs units) are to be regarded as the standard where inch-pound units (or cgs units) are given first, followed by SI units. Where only SI units are given, or where SI units are given followed by inch-pound units (or cgs units), the SI units are to be regarded as standard.
- This standard may involve hazardous materials, operations, and equipments. This standard does not purport to address all of the safety problems associated with its use. It is the responsibility of whoever uses this standard to consult and establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use. Specifically the paint and the propane used in this test method contain materials which, in certain concentrations, may either be flammable or require special handling. Material safety data sheets from the Occupational Safety and Health Administration (OSHA), Department of Transportation (DOT), and

American Conference of Governmental Industrial Hygienists (ACGIH) should be consulted for appropriate precautions. The services of a Certified Safety Professional (CSP) or a Certified Industrial Hygienist (CIH) will assist in establishing prudent practice.

C.2 Summary of Test Method

The method is based on measurement of the 100-Hz electrical resistance between two narrowly spaced stripes of conductive paint applied to a concrete surface. The paint curing is accelerated, and the concrete surface is preconditioned by heating to approximately 120°F (49° C) using either a small infrared propane heater or an electrical blow dryer. The test area is wetted for a short period of time. Excess surface water is removed, and a resistance measurement after four minutes is an indication of the ability of penetrating surface sealers to prevent water penetration or to expel the water from the surface layer. The absolute resistance across the fixed geometry gage is a qualitative measure of the effectiveness of the sealer. Combined with a measurement on uncoated sections of the same concrete, the measurements become semi-quantitative, and the effectiveness of the sealers can be classified as ineffective, borderline effective, or effective.

C.3 Significance and Use

This method can be used to gain an indication of the relative effectiveness of penetrating sealers applied to concrete. It can also be used as a research tool to compare uncoated concrete surface conductivity caused by variations in soluble salts, alkalies, and porosity.

This method is applicable in both field and laboratory, provided that the test surface is almost flat, without major cracks, and that the center of the test area is no closer than approximately 1-inch (25-mm) from the edge of the member or specimen.

C.4 Interferences

The test can be sensitive to surface roughness. Tests cannot be carried out on grooved or tyned (skid-textured) surfaces. Very rough or weathered surfaces may also pose problems. If the end-to-end resistance of the individual sides of the resistance gage cannot be reduced below approximately 125 ohms (DC measurement), even on repeat installation of the gage, roughness, bug-holes, or cracks in the concrete may be the reason.

C.5 Apparatus and Supplies

The required equipment consists of a user-prepared painting mask, conductive spray paint, a small propane infrared heater or an electrical blow dryer, a digital-readout temperature indicator with flexible thermocouple, a standard digital multi-meter, a 100-Hz AC ohm meter, and spring-loaded test leads for one-handed operation.

Mask - The mask for applying the two paint stripes to the concrete is shown in Figure C-1. The overall size of the mask is not critical as long as it can catch some of the over-spray. In use, the mask is centered over a strip of Scotch 3M 218 Fine Line Tape or equivalent 1/8-inch (3-mm) wide. The mask is held to vertical surfaces with a good grade of duct tape 3-inch (75-mm) wide. On horizontal surfaces, a suitable small weight can be used to hold the mask in position.

Paint - A paint suitable for use with this test method is E-KOTE- 40 Silver Conductive Paint or equivalent.

Heater - A suitable portable infrared heater is the Magua-252 Infrared Tool & Heater or equivalent. This heater operates from a standard 14.1-oz (415-ml) propane fuel cylinder. An alternate heater would be either an AC- or DC-operated hand-held blow dryer.

Temperature Indicator - Any suitable thermocouple digital thermometer having a resolution of 1° F (0.5° C) with a flexible, thin wire copper-constantan thermocouple is acceptable. Liquid crystal temperature-indicating labels also can be used, but with less resolution.

Digital Multi-Meter - A digital multi-meter having a DC resistance range of 0 to at least 20 megohms and input impedance of at least 10 megohms is acceptable.

AC Resistance Meter - A suitable 100-Hz AC resistance meter is the Model 400 Solid State 4-Pin Soil Resistance Meter from Nilsson Electrical Laboratory, Inc., New York, NY 10011. The highest measurable resistance of this unit is 1.1 megohms.

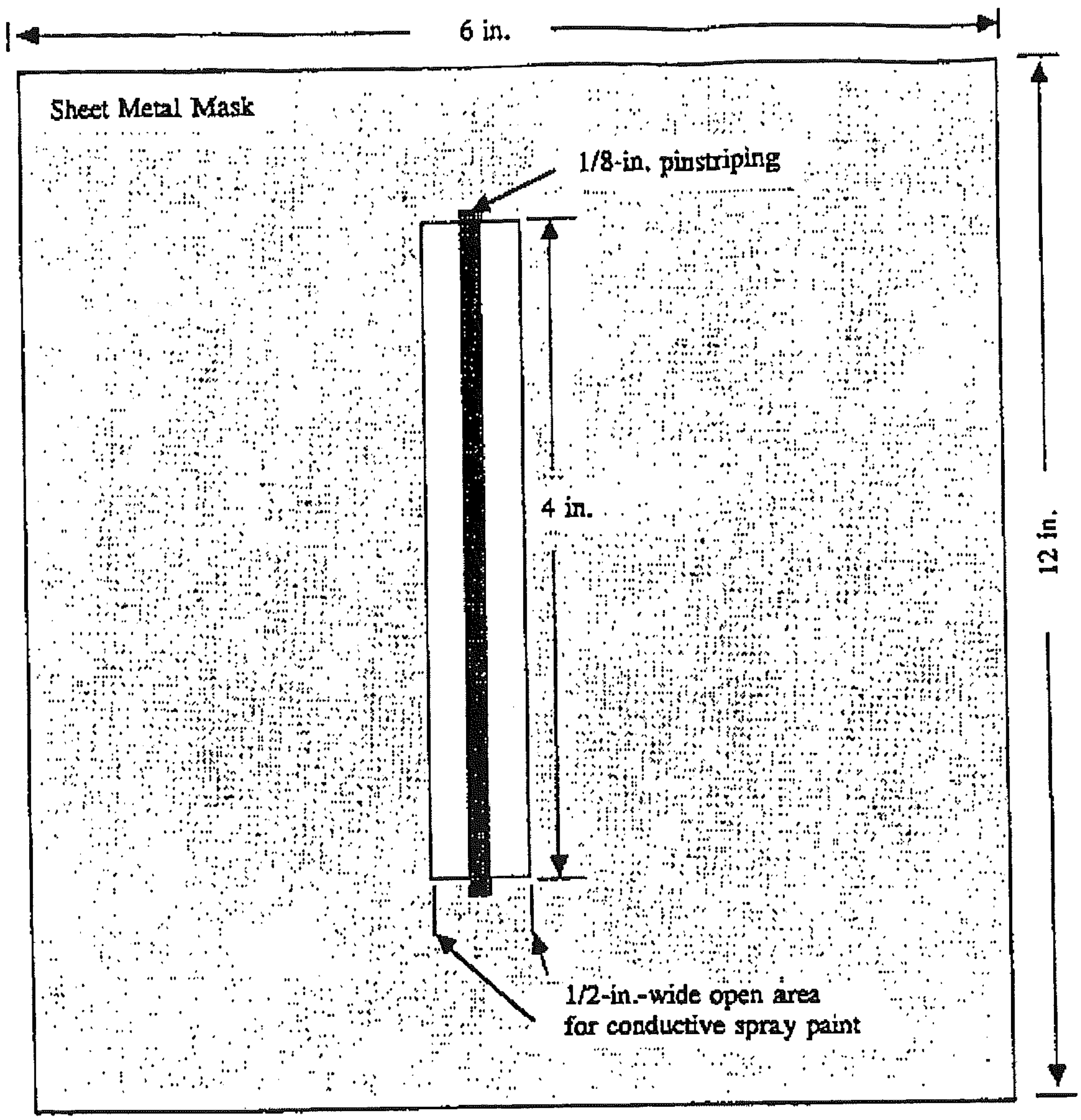
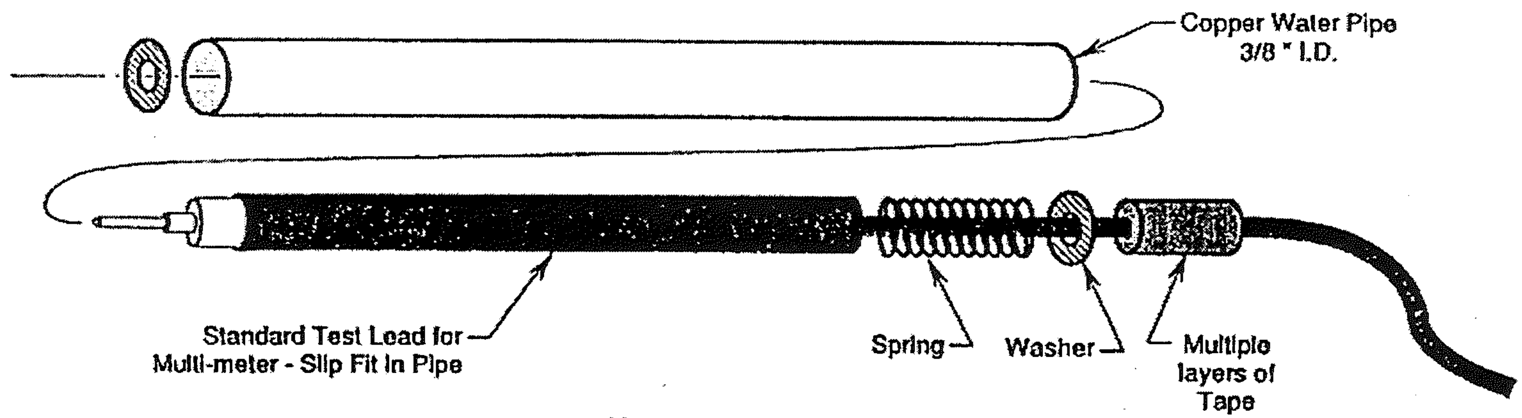


Figure C-1. Mask for production of surface electrodes



Assembly:

1. Insert test lead into pipe.
2. Solder washer to pipe.
3. Tape will act as stop.
4. Tape two assembled pipes together to form a one-handed dual prong test lead.

Figure C-2. One-handed dual prong test lead

Test Lead - Spring-loaded test leads for measuring the electrical resistance of the gage as shown in Figure C-2.

C.6 Sampling

Spacing between Measurements - The spacing between measurements should be consistent with the size of the member being investigated and the intended use of the measurements.

C.7 Procedure

Surface Preparation - The surface must be clean and free from grooves, cracks, and irregularities, which could prevent obtaining a good gage application. The surface must be dry to the touch for the paint gage to bond properly. If the surface is wet or the ambient temperature is near 50 F (10 C), heating to 120 F (49 C) will facilitate gage application. The surface should then be brushed and gently scrubbed with a dry paper towel to remove dust, dirt, or debris prior to testing.

Attaching the Mask - A 6-inch. (152-mm) strip of the fine-line tape is applied to the area to be tested. The tape is pressed onto the concrete by applying heavy thumb pressure from the center and working to the ends of the tape. The metal mask is then centered over the tape. On vertical surfaces, the mask is held in place by four strips of duct tape 3-inch (75-mm) wide. On horizontal surfaces, a small weight can be used to hold the mask in place. The tip of the copper-constantan thermocouple is taped securely with thin transparent tape to the metal mask, next to the slit.

Gage Application - The normal cure time of the paint is 16 hours. To accelerate the cure, use the following procedure. Shake the paint can thoroughly per manufacturer's instructions. Hold can approximately 10-inches (250-mm), or somewhat closer in windy conditions, from the mask surface. Direct the spray near the end of the metal slit. When the paint flow has stabilized, pass the spray lengthwise over the slit six times, alternating the direction at the end of each sweep. The coats should be thin enough to prevent any runoff or seepage under the fine-line tape. Heat the surface with either the infrared heater or a blow dryer for 5 minutes. Control the indicated temperature at 120 F (49 C). Repeat the gage application and the heating cycle two additional times. Remove the mask and the fine line tape.

NOTE 1 - Attempts to make a non-conductive gage acceptable by curing at a higher temperature, even as low as 135 F (57 C), are not recommended. This may cause changes in the concrete or the sealer, making a comparison with normal cure gages invalid. Occasionally, a high-resistance gage can be made conductive by installing one more layer of paint followed by curing at the standard 120 F (49 C).

NOTE 2 - Occasionally, the quality of paint may be the reason for a high end-to-end resistance of the gage. Switching to a new can or batch of paint may be necessary. With the paint used for the development of the test, it was generally found that a total of eight gages could be made reliably from each can. If the sealer, especially of the epoxy type, has not cured adequately, either because of very recent application or low ambient temperature, it may be impossible to prepare a low-resistance gage. This is presumed to be due to remaining solvents or resins bleeding into the paint, preventing a low-resistance path between the conductive pigment particles in the paint.

Preliminary Testing of Gage - Measure the end-to-end DC resistance of the two sides of the gage. Resistances of up to approximately 125 ohms are acceptable. A very good gage will be in the range of 5 to 15 ohms. Record the readings. Measure the DC insulation resistance between the two sides of the gage. Record the reading in megohms. Dry concrete containing low amounts of soluble salts will have a resistance exceeding 20 megohms. Gages having a resistance exceeding 5 megohms can be used (see note 3).

NOTE 3 - The DC insulation resistance (side-to-side) of a gage normally is greater than 20 megohms. Side-to-side DC resistances as low as 2.5 megohms can be acceptable where an approximate error of 20 percent in the actual 100 Hz resistance measurement will not affect the conclusion as to the acceptability of a particular sealer. Low insulation resistances may be caused by excess levels of alkalies or soluble salts in or on the concrete. It may be possible to wash off a sufficient amount to produce gages of adequate insulation resistance.

AC Resistance at 100 Hz - Wet the gage with potable water and keep it wet for five minutes. Immediately dry the gage by pressing a dry, folded paper towel against the gage for five seconds. Follow this by gently wiping the gage in a lengthwise direction using a crumpled, dry paper towel. Take the AC resistance reading four minutes after wiping the gage.

NOTE 4 - A vertical area can be kept wet by holding a wet sponge over the gage and pouring water on the top of the sponge.

NOTE 5 - The Nilsson meter can be held temporarily in the active low-sensitivity measurement mode by attaching a rubber band between the toggle switch and the left locking mechanism.

NOTE 6 - Optional, additional information can be obtained by taking resistance readings at 0, 1, 2, 3, 4, and 10 minutes.

C.8 Interpretation of Results

Use Table C-1 to interpret the results. These values were selected as representative from gage measurements both on field and laboratory concretes.

Table C-1. Categories of Relative Effectiveness of Sealers.

100 Hz Resistance (kiloohms)	Relative Effectiveness of Sealer (Category)
0 to 200	Ineffective (or not sealed)
200 to 400	Borderline effective
Over 400	Effective

C.9 Report

The report shall consist of at least the following:

- Location of test or identification of specimen,
- Specimen history or recent environmental field conditions,
- Conditions at time of test (air temperature, concrete temperature, RH, wind speed, etc.),
- Pre-conditioning of test area (if used),
- Preliminary gage test results,
- AC resistance at four minutes and category, and
- Optional resistance measurements at other time intervals.

C.10 Precision and Bias

Precision - The single-operator within-lab coefficient of variation has been found to be 19percent of the resistance reading. Therefore, results of two properly conducted tests by the same operator on the same material should not differ by more than 54 percent.

Bias - The procedure in this test method for measuring relative effectiveness of penetrating concrete sealers by electrical resistance has no bias because the surface resistance is defined only in terms of this test method.