National Cooperative Highway Research Program

NCHRP Synthesis 209

Sealers For Portland Cement Concrete Highway Facilities

A Synthesis of Highway Practice

Transportation Research Board
National Research Council

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Sealers For Portland Cement Concrete Highway Facilities

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PREFACE

A vast storehouse of information exists on nearly every subject of concern to highway administrators and engineers. Much of this information has resulted from both research and the successful application of solutions to the problems faced by practitioners in their daily work. Because previously there has been no systematic means for compiling such useful information and making it available to the entire highway community, the American Association of State Highway and Transportation Officials has, through the mechanism of the National Cooperative Highway Research Program, authorized the Transportation Research Board to undertake a continuing project to search out and synthesize useful knowledge from all available sources and to prepare documented reports on current practices in the subject areas of concern.

This synthesis series reports on various practices, making specific recommendations where appropriate but without the detailed directions usually found in handbooks or design manuals. Nonetheless, these documents can serve similar purposes, for each is a compendium of the best knowledge available on those measures found to be the most successful in resolving specific problems. The extent to which these reports are useful will be tempered by the user's knowledge and experience in the particular problem area.

FOREWORD

By Staff
Transportation Research Board

This synthesis document will be of interest to materials, maintenance, and bridge engineers, and others responsible for protecting and maintaining portland cement concrete (PCC) roadway surfaces. It will be of special interest to materials research and testing officials, as well as to manufacturers who are concerned with developing and evaluating sealers for PCC highway facilities. The information in this Synthesis is limited to surface-applied liquid sealers that are primarily intended to retard the transmission of water and ions below the roadway surface.

Administrators, engineers, and researchers are continually faced with highway problems on which much information exists, either in the form of reports or in terms of undocumented experience and practice. Unfortunately, this information often is scattered and unevaluated, and, as a consequence, in seeking solutions, full information on what has been learned about a problem frequently is not assembled. Costly research findings may go unused, valuable experience may be overlooked, and full consideration may not be given to available practices for solving or alleviating the problem. In an effort to correct this situation, a continuing NCHRP project, carried out by the Transportation Research Board as the research agency, has the objective of reporting on common highway problems and synthesizing available information. The synthesis reports from this endeavor constitute an NCHRP publication series in which various forms of relevant information are assembled into single, concise documents pertaining to specific highway problems or sets of closely related problems.

This report of the Transportation Research Board provides detailed information on generic concrete sealing materials that may be considered a primer on the topic, describing the various classes of sealers, their chemical characteristics, application to specific needs, and practice and performance characteristics. In addition, information is provided on evaluation and testing, application and costs, and the safety and environmental issues of concern with their use. Also included is a glossary of terms, extensive references, and an appendix that includes materials on a procedure for the estimation of service life and a model sealer specification.

To develop this synthesis in a comprehensive manner and to ensure inclusion of significant knowledge, the Board analyzed available information assembled from numerous sources, including a large number of state highway and transportation departments. A topic panel of experts in the subject area was established to guide the researcher in organizing and evaluating the collected data, and to review the final synthesis report.

This synthesis is an immediately useful document that records practices that were acceptable within the limitations of the knowledge available at the time of its preparation. As the processes of advancement continue, new knowledge can be expected to be added to that now at hand.

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SEALERS FOR PORTLAND CEMENT CONCRETE HIGHWAY FACILITIES

SUMMARY

Careful examination of the technical literature on concrete sealers and responses to detailed questionnaire surveys conducted among highway agencies and sealer manufacturers has produced a rather complete picture of the use of concrete sealers and the associated problem areas.

Surface sealers and coatings are commonly used to protect concrete from aggressive environments. Initially in the highway sphere, the objective in using these materials was to counteract freezing and thawing and deicer scaling damage to concrete. With the advent of air-entraining agents, the primary purpose for sealers changed to preventing or retarding the ingress of chlorides that cause serious damage through corrosion of reinforcing steel. Other, albeit less frequently employed, uses of sealers include providing abrasion resistance (wind, water/ice, and traffic), aesthetics (graffiti-proofing), protection against aggressive chemical agents (e.g., sulfate-bearing groundwater and acid rain), and limiting water ingress to retard deterious reactions (e.g., alkali-silica reactivity). Properly applied and managed, sealers can be an important element in the overall strategy for cost-effective protection and maintenance of new and existing highway facilities.

A large number of sealer products exist, covering a broad range of generic types. Coupled with the present use of numerous and varying product qualification testing procedures and criteria by the various highway agencies, a lack of uniform protocol currently exists regarding sealer approval and use. Qualification tests, in most cases, are not sufficient to properly screen sealer products. A significant proportion of the high degree of variability reported in qualifying concrete sealers by the highway agencies is attributable to the lack of a national standard testing protocol. Likewise, some of the variability in field performance among sealer generic types, and even among products comprising given generic types, results from the misapplication of sealers. However, there are significant differences in capability among the generic types of sealers, and even some differences among products within generic categories.

Beyond sealer qualification testing, there presently is little routine testing done to assure the continued quality of approved products or the quality of field applications, or to assess sealer reapplication needs and product performance in the field. Testing protocols, especially those for qualification testing, need to realistically address field exposure variables to the maximum feasible extent. At present, it appears that only the program developed by Alberta Transportation and Utilities begins to approach fulfilling these needs.

Analysis of the data accumulated in the development of this Synthesis provided interesting insight into the use and performance of concrete sealers. Regarding purported overstatement of sealer penetration depths by sealer manufacturers, a comparison of data from DOTs and manufacturers shows that, in general, this does not occur. Regarding sealer

performance, dual systems (consisting of a penetrating water-repellent primer and a pore-blocking top coat) seem to be superior to other materials for sealing trafficked surfaces such as bridge decks. Organosilicon materials (silanes and siloxanes) generally display good field performance if properly applied to suitable concrete substrates, in spite of laboratory freezing and thawing test performances that would foretell otherwise. The same is true of boiled linseed oil, but in this case it is laboratory absorption and chloride penetration testing that is problematic. Epoxies, acrylics, and gum resins also appear, in general, to perform satisfactorily in the field. Urethanes and chlorinated rubbers generally performed well in laboratory testing, but too few data exist to form opinions on field performance.

The choice of sealer for a job from the list of qualifying products should be rendered on the basis of minimum life-cycle cost. This determination depends on the initial and subsequent costs associated with each candidate material and its prospective service life. Thus, service lives need to be estimated. A procedure developed under the Strategic Highway Research Program (SHRP) to do this is presented.

Recommendations resulting from synthesis of information from the technical literature and surveys of sealer manufacturers and departments of transportation are as follows:

- Develop rational test protocols for:
  - Sealer product qualification (including required application rate),
  - Sealer product quality assurance,
  - Field application quality assurance (including achieved application rate), and
  - Field testing for performance and reapplication needs.
- Develop national data bases for:
  - Acceptable sealer products, based on the recommended test protocols,
  - In-place costs for acceptable sealer products,
  - Observed field service lives (reapplication times) for acceptable sealer products, and
  - The performance of sealers as a function of the type of application and concrete substrate properties.
- Sealer manufacturers need to press research efforts into the development of sealers and their carriers or diluents that meet the volatile organic compound (VOC) limitations anticipated under projected federal regulations.

Because of the large number of products available and the time and cost required to test them, there is considerable economic incentive for the establishment of a national data base for sealer products based on uniform testing standards. The consensus test protocols must, of course, be developed and operating first.

CHAPTER ONE

INTRODUCTION

BACKGROUND

Deterioration of portland cement concrete structures usually results from, or is critically dependent on, the ingress of substances through the concrete surface, most importantly water. Water is involved in virtually every form of concrete deterioration—freezing and thawing damage (including popouts and surface scaling), reinforcement corrosion, alkali-aggregate reactions, dissolution, sulfate attack, and carbonation. Other agents involved include gases, such as carbon dioxide (carbonation) and oxygen (reinforcement corrosion), and soluble chemicals, such as chlorides (reinforcement corrosion) and sulfates (sulfate attack). High quality, properly air-entrained concrete will preclude some problems, such as those associated with frost action, and to varying degrees will retard most others. However, to ensure the expected service lives of long-term public works projects such as highway facilities, other measures are needed to combat deterioration associated with the ingress of aggressive substances, most notably the chloride-induced corrosion of reinforcement. One means of preventing reinforcement corrosion is to prevent the ingress of the chloride ions necessary to initiate the corrosion process by sealing the concrete surface. Sealing may also reduce the moisture content (*1*), which increases the resistivity of the concrete. It may also retard the movements of oxygen necessary to depolarize cathodic areas in the corrosion process and carbon dioxide, thus preventing carbonation, which lowers pH.

With the obvious potential for improving concrete durability, it is not surprising that interest in the use of sealers began as far back as the 1930s. As awareness has grown since the 1960s regarding the severity of the reinforcement corrosion problem, the interest in and use of sealers has expanded exponentially. In the literature review conducted for this Synthesis, 58 percent of 83 papers and technical reports that were identified on the subject of concrete sealers were published in the last 5 years (42 percent in the last 3 years).

Accompanying the surging interest in the use of sealers, there has been a rapid increase in the types of sealers and commercial products, along with the number of manufacturers producing them. The literature search and questionnaire surveys conducted in conjunction with this Synthesis identified 409 concrete sealer products and 169 manufacturing firms that produce them, and it is recognized that these lists are far from complete. This situation has created a host of problems (*2,3*). To begin, the plethora of sealer products commercially available is overwhelming to the user. Furthermore, some two dozen or more types exist (depending on categorization) regarding mechanisms of action, chemical structure, and diluent used. There is no consensus on acceptable test methods for evaluating sealers (*3*), and conflicting performance reports are commonplace. Even widely varying performance among products from the same generic class is not uncommon. Manufacturers' claims are sometimes exaggerated and often unsupported. Amid this confusion there clearly exist products that do not work, as well as misapplications of products by users (*4,5*). While most highway agencies attempt to compile approved product lists based on experience or limited testing, the lack of appropriate testing protocols linked to actual field conditions and the almost constant barrage of new products and variants has made this task difficult (*6*). The key factor is the need for development and wide acceptance of rational test methods closely tied to specific sealing needs and field conditions.

In spite of the perceived problems, sealing is one of few options available for maintaining existing structures and the most economical when a 20 to 50 percent extension in service life is acceptable (*7*).

PURPOSE

The primary purpose of this Synthesis is to summarize what is known about sealer use and technology and to provide direction for further advances. This will be accomplished by first summarizing existing information. Analysis of that data base will identify problem areas and knowledge gaps. Synthesis of the existing information will provide the basis for recommendations regarding rational practices. Deficiencies that remain will provide recommendations for future research.

SCOPE

The scope of this Synthesis is limited to surface applied liquid sealers primarily intended to retard the transmission of water and ions. This specifically excludes internal sealing methods (such as wax beads) and impregnation procedures involving the use of applied potential gradients (electrical, pressure, hygrometric, or thermal) to induce penetration of sealers into concrete. Also, undiluted epoxies and other viscous polymers containing aggregates used on traffic surfaces as overlays will not generally be considered except for the occasional need for completeness. Finally, bitumastic materials, which are commonplace as overlay components on traffic surfaces or as below-grade concrete sealant, and cementitious coatings are not included in this Synthesis.

APPROACH

The approach to acquisition of the data that form the basis of this Synthesis consists, in broad terms, of a search of the technical literature on the subject and the use of survey questionnaires to obtain current information from practitioners and vendors. The literature search consisted, initially, of recently published or work-in-progress information from individuals known to be knowledgeable or currently involved in research on concrete sealers. Additional sources of information were identified through the

Transportation Research Information System (TRIS), and a manual search. Potential sources cited in the TRIS search were acquired. Citations appearing in all sources acquired were subjects of follow-up searches. Some transportation agency reports, test methods, and specifications were also received with questionnaire responses.

The other major factor in data acquisition consisted of surveys. Information from prior survey results was obtained from the literature. In two cases, raw data were obtained from the individuals who conducted the surveys. The prior surveys studied are:

- A 1977 survey of state highway agencies for preparation of NCHRP Synthesis of Highway Practice 57, which pertains to use of sealers on bridge decks only (*8*);
- A survey of state highway agencies and chemical or paint manufacturers reported in NCHRP Report 244 and issued in 1981 (*9*);
- A 1986 survey of state highway agencies covering sealer use on bridge decks only, which was reported in NCHRP Report 297 (*10*);
- A 1989 survey, again related to bridge decks, distributed to state and provincial highway agencies, selected turnpike authorities, directors of technology transfer centers, and selected material suppliers in conjunction with SHRP Project C-103 (*11*);
- A 1989 survey of state and Canadian provincial highway agencies showing the extent of sealer use on bridge decks, which was also carried out under SHRP Project C-103 (*12*); and
- A third 1989 survey emanating from the SHRP activities (Project C-101) that surveyed U.S. state and Canadian provincial highway agencies in detail on all aspects of sealer use (*2*).

Finally, two questionnaire surveys were conducted during the preparation of this synthesis. One, directed at state and provincial highway agencies in the United States and Canada, was a follow-up on the last of the previous surveys listed. The intent was to update information and to fill gaps in the areas of safety, environmental considerations, costs, and testing procedures. Testing reports and field study reports were also solicited. The second questionnaire was directed at sealer manufacturers in the United States. The purpose was to obtain information on the generic types of sealers on the market, types and amounts of diluents or carriers used, costs, application rates, application methods, and product testing data. Material safety data sheets (MSDS) were also requested.

Discussions involving the findings from the questionnaire surveys appear primarily in Chapters 3, 5, and 6, and to a lesser degree in Chapter 4. The highway agency (DOT) questionnaire is reproduced in Appendix A, accompanied by tabulations that summarize the responses. The manufacturer's questionnaire is reproduced in Appendix B, accompanied by summary tabulations of the responses.

CHAPTER TWO

CONCRETE SEALING MATERIALS

CLASSES OF SEALERS

Reflecting the general confusion regarding concrete sealers, there is no existing consensus on how sealers should be classified. The most common approach is to use two classes—penetrants and coatings (*13,14*) where penetrants are generally considered to be vapor transmissible while coatings are not or are appreciably less so (*15,16*). Some prefer to divide penetrants into water-repellent (vapor transmissible) and pore-blocking types, reserving the term coatings for high solids polymers that form relatively thick surface coatings (*17,18*). The American Concrete Institute (ACI) 201.2R-77, "Guide to Durable Concrete" (*19*) recommends two classes of coatings based on surface coating thickness, applicable to concrete highway structures: Class I—"Surface Water Repellent" (thickness (0.13 mm (5 mils)) and Class II—"Plastic and Elastomeric" (thickness (0.13-0.26 mm (5-10 mils)).

The term "penetrant" is particularly troublesome because it involves a somewhat qualitative measure that varies as a function of conditions that often are not controllable (temperature and moisture, principally). Therefore, the following classification scheme is adopted for this synthesis: water repellent, pore blocker, and barrier coat.

In this system, "water repellent" refers to those materials that penetrate concrete pores to some degree and coat pore walls rendering them hydrophobic. The condition of hydrophobicity is defined by a contact angle between water and the concrete surface that is between 90° and 180° (i.e., water beads up) (*20*). Under this condition, liquid water and any ions that it contains (e.g., chloride and sulfate) cannot penetrate concrete pores, but gases and vapors can. This mechanism appears to be especially attractive because it can, at least theoretically, promote drying of the concrete over time. It can do this by first preventing the entrance of liquid water into treated pores because of the large contact angles for water menisci on the treated surfaces. Second, any water in the pores beyond the treated zone will evaporate as the vapor pressure of the moisture in the atmosphere (relative humidity) falls below the relative vapor pressures needed to maintain the liquid menisci in the pores. Water cannot be replenished by liquid water due to the water repellency of the pore walls at the surface. According to the Kelvin equation, at an average temperature of 50°F (10°C) and relative humidity of 60 percent, only the capillaries that are smaller than about 4 nm (1.6×10^{-7} in.) can be replenished by capillary condensation. This is the order of magnitude of the smallest capillary pores in hardened cement paste (HCP), which says that, theoretically, all of the continuous capillary pores in concrete could eventually be dried out by this mechanism under the conditions of temperature and humidity assumed here. Experimental evidence supporting this mechanism has been reported (*7*).

Pore blockers are sealers of sufficiently low viscosity to allow them to penetrate the pores in concrete, sealing them while leaving little or no measurable coating on the exterior surface of the concrete. Barrier coatings, on the other hand, are too viscous to penetrate pores to measurable depths, but form surface coatings of significant thickness and block the pores. As will be shown later in this chapter, many chemical types of sealers can be either pore blockers or barrier coatings depending on whether a diluent or solvent is or is not used to reduce viscosity. Also, notice that the barrier coating classification contains many of the same materials used as overlays on traffic surfaces. Overlays, however, are not covered, per se, by this Synthesis. The difference is that the barrier coating class of materials contains no aggregate and is used principally on non-traffic surfaces.

Both pore blockers and barrier coatings restrict the passage of water vapor, reducing drying of concrete and creating the possibility for internal stresses resulting from moisture entrapment (e.g., freezing, vapor pressure, osmotic pressure).

CHEMICAL SPECIES AND MECHANISMS OF ACTION

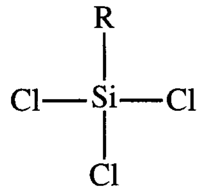
The varieties of materials that are presently used as concrete sealers, in order of decreasing current popularity as indicated in the questionnaire survey by the number of highway agencies using them (see Table A-1, Appendix A), are as follows:

- Silanes, siloxanes, and siliconates
- Epoxies
- Gum resins and mineral gums
- Linseed oil
- Stearates
- Acrylics
- Silicates and fluosilicates
- Urethanes and polyurethanes
- Polyesters
- Chlorinated rubber
- Silicones
- Vinyls.

Each will be discussed in detail in the following subsections.

Silanes, Siloxanes, and Siliconates

These materials fall under the general chemical classification of organosilicon compounds. Within that classification, silanes, siloxanes, and siliconates are usually considered together because all have three silicon functional groups and one organofunctional group (*13*). This is best illustrated by the raw material from which all three are produced—chlorosilane:

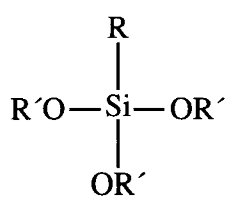


Here the three silicon functional groups are occupied by chlorine and the organofunctional group (R) consists of an aliphatic (straight or branched-chain) hydrocarbon. This is sometimes referred to as the "T" structure group of the organosilicon materials.

Silanes, siloxanes, and siliconates consist of molecules that bond to hydrated cement paste substrate and to each other by means of the silicon functional groups, and provide a hydrophobic (water-repellent) layer on pore walls from the exposed organofunctional groups. Thus, they fall into the water-repellent class of concrete sealers.

The nomenclature and descriptions for the organosilicon materials are the most confusing and improperly applied of all the concrete sealers. The situation can be clarified by describing the steps involved in the manufacture and use of the T structure organosilicons because, as already noted, they are all derived from the same substance — chlorosilane. Figure 1, based on a synthesis of the technical literature (*7,21-30*), presents the framework for discussion in the form of a flow diagram.

Silanes and siloxanes are, by far, more widely used as concrete sealers than siliconates and, in preparation, follow the same general chemical reaction shown along the lower branch of the flow diagram emanating from chlorosilane. If no water is used in the manufacturing process, i.e., $(n - 1) = 0$, then $n = 1$. In that case, three moles of alcohol (R′OH), i.e., $n + 2 = 3$, are combined with one mole of chlorosilane to form one mole of silane:



The correct nomenclature for this class of substance is alkyl trialkoxy silane where "alkyl" refers to the organofunctional group R, the part of the molecule responsible for water-repellent properties, and "alkoxy" pertains to the three O-R′ silicon functional groups. The correct specific chemical name depends on the natures of the R and R′ groups. For silanes used in sealing concrete, methyl alcohol (CH_3OH) is generally used. Therefore, R′ is usually CH_3 and the "trialkoxy" term becomes the more specific "trimethoxy." Sometimes ethyl alcohol is used and then the specific version of the "trialkoxy" term becomes "triethoxy." The organofunctional group, R, carries over from the chlorosilane raw material. It is a normal straight (n–) or branched (iso–) aliphatic (chain) hydrocarbon usually having either four (butyl) or eight (octyl) carbon atoms. The nature of the organofunctional (R) group is critical to the performance of the silane as a penetrating water repellent because it dictates the degree of hydrophobicity and long-term durability (alkali resistance), both increasing with increasing chain length and with chain branching (iso–). For example, the branched chain isobutyl, at half the size, provides about the same degree of water repellency as the straight chain n-octyl group (*31*). The penetrability of the silane depends primarily on the size of the alkoxy (R′) silicon functional groups. The methoxy group provides faster penetration than the larger ethoxy group, but it is also more reactive, which impedes penetration, and it is more volatile. On balance, it appears to be about an even trade-off relative to penetration, and the methoxy group seems to be the silicon functional group of choice (as previously noted). Because of these considerations, the compromise that results in the most effective, and most widely used, silane is iso-butyl trimethoxy silane. The major disadvantage of that formulation is the high volatility that necessitates fairly high concentrations of the expensive silane in the diluent, or carrier (usually isopropyl alcohol).

Continuing the flow diagram in Figure 1, when the silane is applied to concrete, it and its carrier are absorbed into the pore system of the concrete. The carrier evaporates and the silane reacts with moisture present in the concrete, 3 moles of water $(n + 2)$ per mole of silane, producing one mole of silanol and 3 moles of alcohol of the same variety used in the manufacture of the silane. This hydrolysis reaction requires the presence of a highly alkaline environment that acts as a catalyst. The silanol produced is an intermediate stage in the process and is actually indiscernible because of its instability. Finally, the unstable silanol reacts with itself (condensation) and with the hydrated cement paste substrate to form a chemically bonded lining in the pores of the concrete, which has a water-repellent surface due to the protruding organofunctional groups.

Siloxane follows the same path as silane of the flow diagram in Figure 1. The only difference is that water is added during the manufacturing process. Therefore, n must be >1 and the siloxane molecule will involve the joining of two or more mers, or basic repetitive silane units (dimer, trimer, ... etc., polymer). The order (n) is dependent on the amount of water involved. The higher the order, the lower the volatility of the siloxane, but the less penetrable in concrete. Consequently, siloxanes used as penetrating sealants for concrete usually use short chains (two to five units) referred to as "oligomerous" siloxanes. Chains longer than this are referred to as "polymeric" siloxanes. The latter are suitable only as non-penetrating, pore-blocking surface coatings. The nomenclature applied to siloxanes is exactly analogous to that for silanes, and the choice of siliconfunctional and organofunctional groups is the same and for identical reasons. Therefore, commonly used siloxane formulations include oligomerous iso-butyl trimethoxy siloxane and oligomerous iso-octyl trimethoxy siloxane.

Notice in Figure 1 that siloxanes react with moisture and the hydrated cement paste in exactly the same manner as silanes do, resulting in the same water-repellent pore surface coatings. The main differences are that siloxanes are practically non-volatile and therefore require much lower concentrations to achieve complete pore coatings, but they do not penetrate as deeply because of their larger molecular size. The carrier most commonly used for siloxanes is mineral spirits.

Siliconates, more properly alkali metal siliconates, are produced by reacting chlorosilane with water and alkali metal hydroxide (MOH) as shown in Figure 1. Alkali metal siliconates are water soluble and have indefinite storage stability. Their main disadvantage is that after application to concrete, a neutralization step involving carbonic acid or carbonation by carbon dioxide from the atmosphere is necessary to extract the alkali metal as the metal carbonate, converting the siliconate to silanol. From that point on, the process is exactly analogous with silane or siloxane. In practice, potassium hydroxide is usually used in the production of siliconates rather than sodium hydroxide because potash (K_2CO_3)

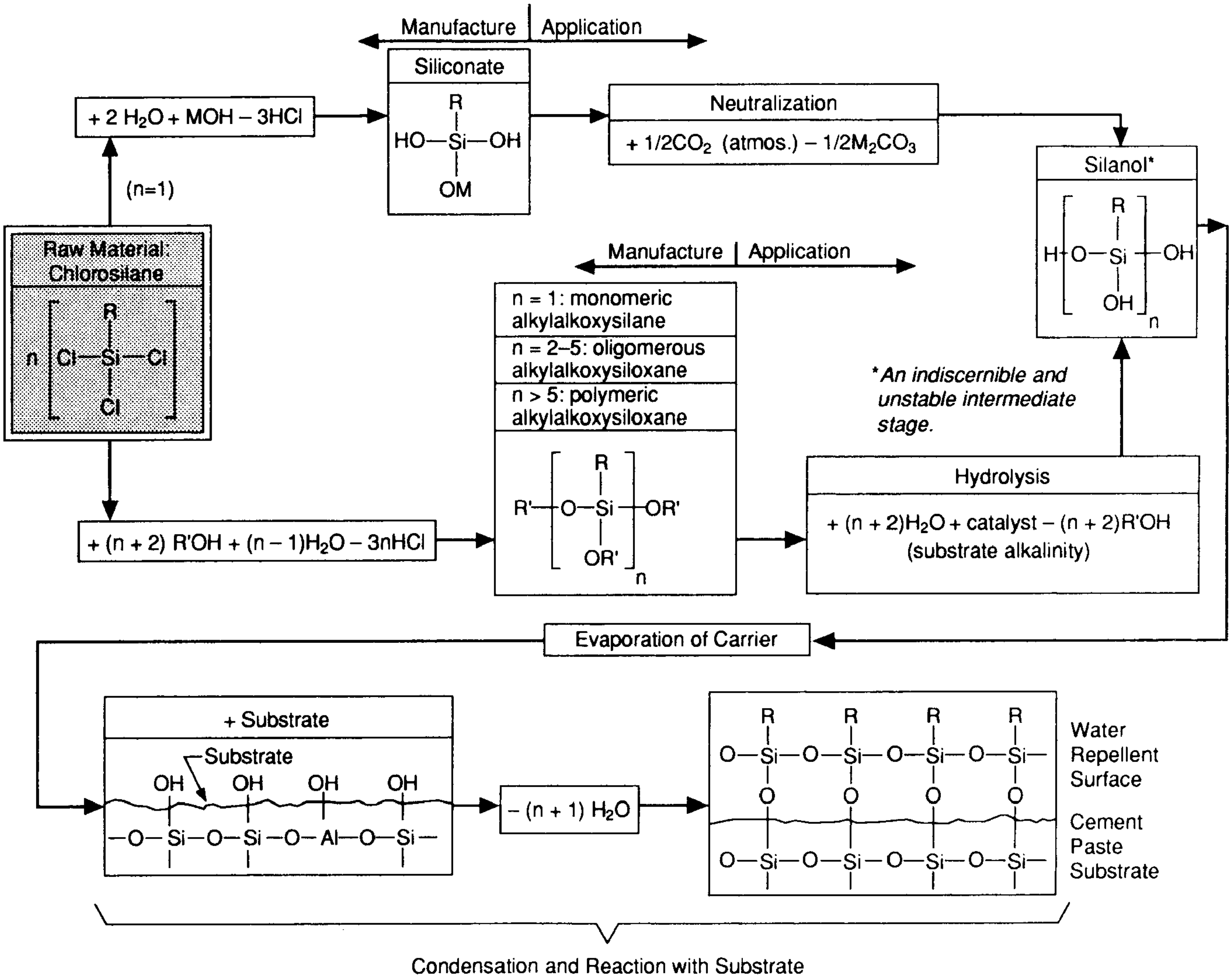


Figure 1 Reactions involved in the manufacture and application of "T" structure organosilicon compounds (siliconates, silanes, and siloxanes).

formed during the neutralization step is less voluminous than soda ($Na_2CO_3 \cdot 10\ H_2O$). Methyl and propyl siliconates are available with the latter being more hydrophobic and more resistant to alkali attack. Unneutralized siliconate can be flushed away with water, but excess siliconate that is neutralized will leave a white deposit (aesthetics). Usually siliconates are used for waterproofing manufactured items where there are better controls in applications procedures (*23*).

It is important to notice that silanes, siloxanes, and siliconates all provide thin water-repelling coatings on the inside pore walls in concrete. This effectively excludes liquid water and the undesirable ionic substances that it carries (chlorides, sulfates) while allowing passage of water vapor and other gases.

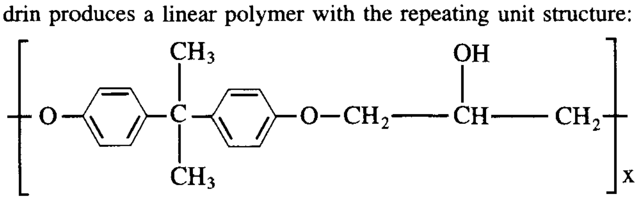
The purposes for the carrier (or diluent, or solvent) used with concrete sealers are to form a stable solution of sufficiently low viscosity to distribute the active ingredient and facilitate its penetration of the concrete substrate (*31*). The carriers, or diluents, used with silanes, siloxanes, and siliconates vary (see Table B-1, Appendix B). As noted earlier, the most common diluent used with silanes is isopropyl alcohol, although mineral spirits, methyl alcohol, ethyl alcohol, and even water are used. The same diluents are used with siloxanes, but mineral spirits appears to be preferred in this instance. As noted, siliconates are diluted in water. With environmental regulations becoming increasingly stringent with regard to the volatile organic compound (VOC) content of commercial products (see Chapter 6), there would appear little doubt that water and exempt solvents will be the diluents for sealers of the future. As mentioned, water-borne silane and siloxane sealers are now commercially available. A conflict may seem to exist, however, in using water as a carrier because it reacts with silane and siloxane in the curing process (see Figure 1). The explanation is that using either emulsion technology or dispersal of the sealer in water immediately prior to application precludes premature reaction with water.

The amount of carrier used also varies by type. Data from the questionnaire sent to sealer manufacturers for this Synthesis (see Appendix B) revealed that the carrier content for available silane products varies from 0 to 90 percent by weight, but most are either

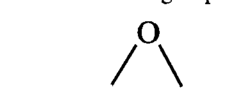
60 percent (53 percent of products) or 80 percent (35 percent of products). For siloxanes, the carrier content varies from 60 to 92 percent, but most (87 percent of products) fall in the range of 80 to 90 percent by weight. The carrier content of siliconates is typically about 70 percent by weight (*9*). The quantity of active ingredient (i.e., the complement of the quantity of carrier) is a function of the internal specific surface of the concrete (pore surface area per unit of pore volume), the quantity of active ingredient required per unit of pore surface area, and losses (primarily evaporation of the active ingredient). As noted earlier the differences in volatility of the active ingredient primarily necessitate the higher concentrations of silane (typically 40 percent) versus siloxane (typically 10 or 15 percent). The use of very high active ingredient content silane (essentially without a carrier) has recently been shown to significantly improve the performance of the sealer (*3,32*). This is covered in greater detail in Chapter 3.

Epoxies

There are many types of epoxies. The type most commonly used as a concrete sealer is based on the reaction product of bisphenol A (diphenylolpropane) and epichlorohydrin. The family of materials based on this reaction can be transformed into thermoset polymers by reactions with curing agents. The curing agents most commonly used are aliphatic polyamines and their derivatives (e.g., diethylenetriamine). Others include amine adducts, amido-amines, and polyamides. The reaction between bisphenol A and epichlorohydrin produces a linear polymer with the repeating unit structure:



having highly reactive terminal end groups ("epoxide" group):



The curing agent, used at the time the epoxy is mixed for application, produces a 3-dimensional polymer by cross-linking the chains (*33-37*).

Epoxies are highly viscous and generally diluted with solvents or prepared in emulsion form with water to facilitate their use as concrete sealers. If the concentration of epoxy in the solution is greater than about 50 percent, the sealer will perform as a barrier coat. That is, it will not perceptibly penetrate the pores of the concrete substrate but will exist as a discernible coating on the exterior surface. When diluted to less than about 50 percent active ingredient by solvents or water emulsions (according to manufacturers' data), some penetration of concrete pores (albeit very small) may occur and the sealer can be classified as a "pore blocker." This is based on the need to reduce the viscosity of the sealer to less than 0.5 Pa-s (500 cps) @ 25°C (77°F) (*25*). The manufacturers' survey data for 10 epoxy sealer products gave a mean active ingredients content of 47 percent (range 15 to 75 percent) (see Table B-1, Appendix B). The viscosities ranged from 0.005 to 0.070 Pa-s (5 to 70 cps) @ 25°C (77°F) for active ingredient contents of 15 to 50 percent (by volume), respectively. In general, solvent systems are more penetrating than emulsion systems because of their lower viscosities (*18*).

Unlike the organosilicon compounds, epoxies do not react with the concrete substrate; they preclude the entrance of water and chloride by blocking pores rather than by creating hydrophobic surfaces. Epoxies display low-order shrinkage on cure, have no by-products of cure, adhere well to concrete, are very tough and durable, provide excellent resistance to acids, bases, and solvents, resist abrasion well, and have good anti-carbonation properties. However, they are subject to embrittlement in long-term aging and chalking from ultraviolet (UV) exposure (*18,34,35,37,38*). Also, recoatability is poor. If used as barrier coatings on traffic surfaces, undiluted (100 percent solids) epoxies are slippery unless they contain an aggregate for skid resistance (i.e., an overlay) (*38*). However, adequate skid resistance may be attained on tined or grooved surfaces for solvent- or water-dispersed epoxies (*39*).

Gum Resins and Mineral Gums

This broad and rather ill-defined category of concrete sealers turned out to be third in terms of apparent use by highway agencies, as indicated by the questionnaire poll conducted for this Synthesis (see Table A-1, Appendix A). Gum resins are solid or semi-solid, viscous hydrocarbon materials. They can be synthetic or natural. Natural gum resins originating from secretions of certain plants and trees include rosin, amber, pine tar, and pitch (*37*). Mineral gums are variously defined as "paraffin wax base dissolved in mineral spirits" (*38*) and "swelling clay derivatives (usually suspended in a solvent)" (*37*). The commercial products that fall into this class are proprietary, and chemical descriptions of specific ingredients are closely guarded trade secrets. However, it can be stated fairly safely that the sealers in this category perform as pore blockers. Even the "clay derivative" type reportedly "expands in the presence of moisture to prevent moisture intrusion" (*37*), which implies pore-blocking action. From information in manufacturer's literature, it appears that the solids content is 30 to 40 percent by volume and the favored solvent is mineral spirits.

Linseed Oil

The use of linseed oil dates from the beginning of the use of sealers on concrete (*40*). Of the highway agencies responding to the questionnaire that use sealers at all, 28 percent permit the use of linseed oil. Fifteen percent use linseed oil exclusively (see Table A-1, Appendix A).

Linseed oil is a vegetable oil produced from flaxseed and consists of a mixture of organic acid triglycerides (i.e., the esters from reactions between fatty acids and glycerol). The primary glycerides involved are those of the unsaturated organic acids linolenic (48 percent), linoleic (24 percent), and oleic (19 percent). The remainder is composed of the glycerides of the saturated fatty acids palmitic (5 percent) and stearic (3 percent) (*41*). The parenthetical quantities represent the typical composition. Linseed oil is a drying oil that hardens by oxidative polymerization. However, the process is exceedingly slow with raw linseed oil. Therefore, raw linseed oil is processed by boiling over mild oxidizers to produce "boiled" linseed oil that polymerizes more rapidly than raw linseed oil when exposed to atmospheric oxygen. Since boiled linseed oil is quite viscous, it is diluted in half with mineral spirits, kerosene, or

Stoddard solvent before being applied as a sealer for concrete. Linseed oil, which is a pore-blocking type of sealer (*38*), is also available as a water-based emulsion.

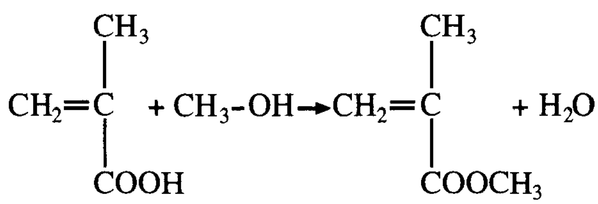
Concerns have been expressed that linseed oil softens and deteriorates concrete and attacks it by reacting with the free lime in a saponification reaction (*13,38*). The softening, which is observed sometimes, is temporary and in a short amount of time, surface hardness returns to or exceeds that of untreated concrete (*42*). This effect, which comes into play in the poor performance that is observed sometimes in laboratory testing with linseed oil treated concrete surfaces, will be discussed in detail under the subject of sealer performance in Chapter 3.

Stearates

Stearate-based concrete sealers are soaps or metallic salts derived from stearic acid or other fatty acids and dissolved in solvents (*37,38*). Stearates fall in the classification of water repellents and are relatively inexpensive and easy to use. However, they hydrolyze rather quickly in the presence of alkalinity in concrete, losing water repellency and becoming ineffective (*38*). They also display poor resistance to UV radiation and weathering.

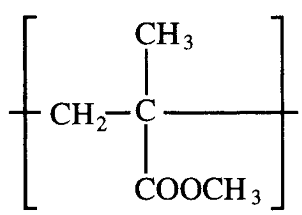
Acrylics

Acrylics are polymers or copolymers of acrylic acid, methacrylic acid, esters of those acids, or acrylonitrile (*17,33,37,38*). For example, methyl methacrylate is the ester that results from the reaction between methacrylic acid and methanol:



Methacrylic Acid + Methanol = Methyl Methacrylate + Water

Opening of the double bond in the methyl methacrylate by means of a suitable initiator (e.g., benzoyl peroxide) produces addition- (vinyl-) polymerization of polymethyl methacrylate, one of the most widely used acrylic polymers, which has the following repetitive unit (*36,43*):



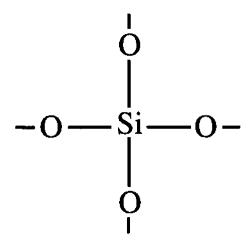
Methyl methacrylate is probably the most common base for acrylic concrete sealers, but because so many formulations are trade secrets, it is difficult to be certain. In addition to strong oxidizers (peroxides) to initiate polymerization, chemical polymerization promoters (usually metal carboxylates) are also used.

Because methyl methacrylate has a low viscosity (about that of water), it can penetrate dry concrete without using a carrier or solvent. More viscous acrylics will usually be diluted with xylene or mineral spirits. Water-based acrylic latexes, which have also been used as concrete sealers, constitute an interesting subclass of sealer in that they are "breathable" (like water repellents), but function as barrier coatings to liquid water. The non-carrier and solvent-based acrylics are generally pore blockers (except for the high molecular weight acrylics that may act as barrier coatings) and vapor transmittance decreases going from pore blocker to barrier coating and with increasing solids content and coating thickness.

In general, acrylics display good resistance to weathering (UV exposure), most chemicals (except certain organic solvents), water and aqueous salt solutions, and acids and bases of moderate concentration (*37*).

Silicates and Fluosilicates

Silicates and fluosilicates are silicon-based sealers that, unlike silanes, siloxanes, and siliconates, contain no organofunctional groups. The lattice unit of silicate compounds, called "Q"-structure (*31*) is:



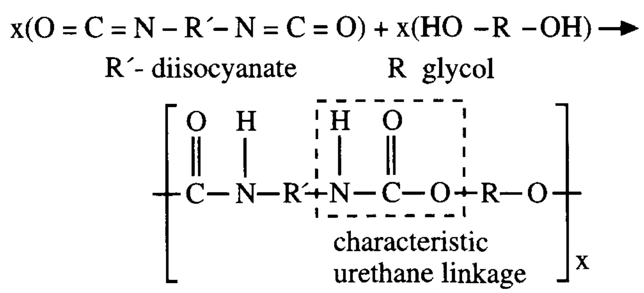
In this system, the element silicon is the inorganic analog of carbon in organic chemical compounds. The range of silicates includes sodium silicate (water-soluble) and ethyl silicate (soluble in organic solvents). Most, if not all, of the silicates used as concrete sealers are water-soluble inorganic silicates. Sodium silicate (water glass), having the variable chemical formula $Na_2O \cdot xSiO_2$ (x = 3 – 5), is most commonly used. Fluosilicates are similar to silicates except that oxygen is replaced with fluorine.

The reactions of silicates and fluosilicates with hydrated cement paste products are apparently not well understood; the technical literature describes various scenarios. One publication states that silicates function as sealers by filling pore structures with precipitated silica (SiO_2) (*31*). A second reports that silicates react with soluble calcium compounds (principally calcium hydroxide) in concrete to form non-water-soluble complex calcium silicates (*38*). Another suggests that silicates form an expansive gel of the same type formed in alkali-silica reactions, which acts as a sealer by swelling in pores in the presence of moisture (*15*). In any case, it seems quite certain that silicates would be classified as pore blockers.

Silicates and fluosilicates are applied to concrete as solutions in water. According to the questionnaire responses, sodium silicate is the type most commonly used (72 percent), with potassium silicate and the fluosilicates following (at 14 percent each).

Urethanes (Polyurethanes)

Urethanes are reactive resins resulting from reactions of isocyanates with either polyols (polyfunctional alcohols) (*15,17,33,34,36*) or low molecular weight polyesters or polyethers (*43*). For example, consider the reaction between a diisocyanate and a diol (or glycol) (*36*):

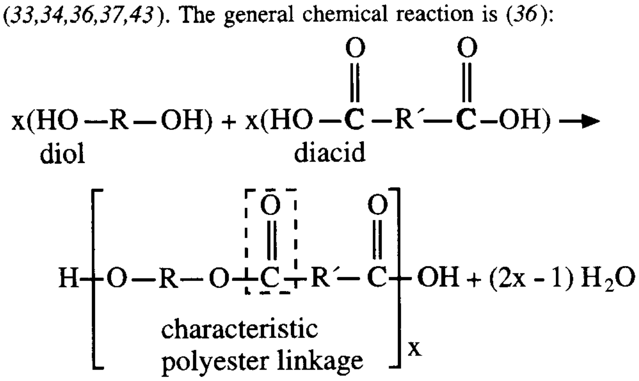


In polymerization parlance, this is a linear condensation reaction (with the water retained). A wide range of resins results from the variety of possible reactants. These are collectively referred to as urethanes.

Urethanes are provided as the conventional two-component (resin-hardener) system or as a one-component system where curing is initiated by atmospheric moisture vapor (*33,34*). The two-component systems usually have better chemical and physical properties. In application and physical properties, urethanes are similar to epoxies, except they are more flexible (*38*). Also, the single component type, which cures by reacting with water vapor in the air, is highly moisture sensitive and must be applied to dry surfaces. This is not a problem with the two-component type of polyurethanes. Like epoxies, undiluted urethanes fall into the class of barrier coatings, but can be made to penetrate pores as pore blockers if diluted with organic solvents. Mineral spirits, xylene, or toluene are usually used for this purpose with urethanes.

Polyesters

Polyesters are products of reaction between difunctional alcohols (diols) and anhydrides of dibasic organic acids (*33,34,36,37,43*). The general chemical reaction is (*36*):



Like the urethanes, polyesters constitute a large group of synthetic resins. The two most commonly used as concrete sealers are based on a reaction either between maleic (a dibasic acid) anhydride and bisphenol A (diphenyl propane, a diol) or acrylic acid and epoxy (vinyl ester) (*34*). These resins are mixed half and half with styrene monomer to reduce viscosity. The polymerization reaction is activated at the time of use by adding a peroxide initiator (usually benzoyl peroxide) and a promoter (e.g., dimethyl analine) (*34*).

Like epoxies and urethanes, undiluted polyesters result in surface barrier coatings, but organic solvents can be used to reduce viscosity and permit pore penetration and, hence, pore-blocking action.

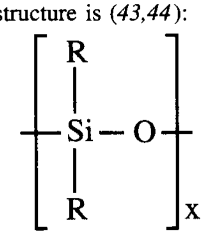
Properties of polyesters are similar to epoxies and urethanes. They display excellent resistance to chemicals, moisture transmittance, and temperature (to 400°F) and must be applied to clean, dry surfaces.

Chlorinated Rubber

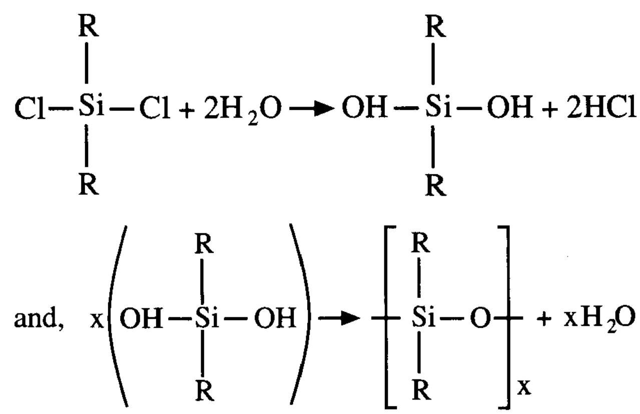
Chlorinated rubber is produced by chlorinating polyisoprene rubber to the point where it is no longer resilient and elastic (*34,37*). The chlorinated rubber is dissolved in an organic solvent and hardens by solvent evaporation (*37*). It is generally used as a barrier coating, but with sufficient dilution by organic solvents, it can also be used as a pore blocker. It is also sensitive to UV radiation and if subject to solar rays as a coating, it must contain a UV absorber (*18,33,34,37*). Chlorinated rubber has excellent resistance to alkalies, moisture, and abrasion (*33,34,37*), and adheres to concrete well (*37*).

Silicones

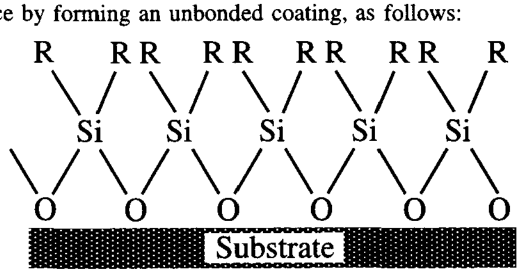
Silicones, the third group of silicon-based materials used as concrete sealers, contain two silicon functional and two organofunctional groups (referred to as the "D" structure) (*31*). The basic repeating unit of this structure is (*43,44*):



Silicone is made by polycondensation of polyfunctional silanols produced by hydrolysis of corresponding chlorosilanes (*43*), as follows:



According to one source, silicones do not form permanent chemical bonds with the hydrated cement paste substrate (as do the "T" structure organosilicons) (*31*). Rather, they provide a hydrophobic surface by forming an unbonded coating, as follows:



Another source describes this as "oxygen bonding" to hydrated silicates in the substrate (*17*). However, a third source indicates that after evaporation of the solvent, silanol groups still remaining from the condensation step (the second of the two chemical equations above) will react with active groups of the substrate, forming chemical bonds (*23*). This would have to occur simultaneously with the condensation reaction.

As was the case with silanes, siloxanes, and siliconates, the size and nature (branched or straight chain) of the organofunctional group profoundly affects water repellency and alkali resistance of the sealer.

Silicones are normally marketed as 5 percent solutions in organic solvents or water. The solvent used has a marked effect on penetrating power (*23*), with organic solvents being better than water (*17*). The water solution type is a sodium resinate and the organic solvent type is an unneutralized resin, either partially or completely condensed (*17*). Therefore, it is clear from the preceding discussion that silicones are of the water-repellent class of sealers.

Vinyls

Vinyl polymers based on acrylic and methacrylic acids were considered as a separate category earlier (under the section Acrylics). There may be other vinyl polymers that are used as concrete sealers. One literature source nonspecifically lists "vinyls" as well as "acrylics" in general descriptions of generic types of concrete sealers (*33*). The vinyls are described as applied in solution form of low solids content requiring multiple coatings to obtain adequate film thicknesses. They are further described as having excellent chemical resistance, but may have poor adhesion properties unless used with special primers. Another source states that several types of vinyl polymers have been used for conservation and consolidation of stone, including poly (vinyl chloride), chlorinated-poly (vinyl chloride), and poly (vinyl acetate) (*34*). However, the first two vinyl polymers should not be used on concrete because chloride ions released by photochemical reactions will attack reinforcing steel (*34*). Polyvinyl acetate is usually applied as a water-based emulsion using emulsion polymerization (*43*).

Polyvinyl butyrate is mentioned as a concrete sealer (*34,37*). It reportedly displays excellent resistance to weathering.

As was the case with acrylics, vinyls may be categorized as barrier coatings or pore blockers depending on the degree to which they are diluted by solvents, or are "breathable" coatings if applied in emulsion form.

BLENDS OF GENERIC TYPES

Mixtures of the aforementioned generic types of concrete sealers are commercially available. The supposed purpose of the blends is to take advantage of certain properties of the individual ingredients to obtain a superior product. Unfortunately, however, the precise natures and proportions of ingredients are invariably trade secrets. Further, no independent test data were uncovered to indicate that any of the mixtures encountered are significantly superior to the best of their component ingredients. However, for completeness, the combinations uncovered in researching this document are as follows:

- Oligomeric alkyl alkoxy siloxane and methyl methacrylate in mineral spirits
- Polysiloxane-silane mix in naphtha solvent
- Aluminum stearate, silane-siloxane blend
- Silane-siloxane mix (3 varieties)
- Acrylic-siloxane blend in water
- Modified oil material, stearates, and silane in solvent
- Modified oil material and mineral gum in mineral spirits (2 varieties)
- Emulsion stain and silane in water.

COMBINATION SYSTEMS

Combination, or dual, systems are generally overlay systems, a subject that is not within the scope of this document. However, the initial component of the combination systems described here is a concrete sealer, and sometimes the top coat will be a pore-blocking penetrant.

Suggested specifications for one three-component combination coating system provided the following requirements for the "sealer-primer" component (*25*):

- Resin should be of low molecular weight/size (effective diameter <0.01 μm (<0.4μ-in.).
- Resin/solvent mix should be of low viscosity <0.001-0.005 Pa-s (<1-5 cps).
- Resin/solvent mix should retain fluidity for 60 to 180 min to allow penetration of pores ≤0.1μm (≤0.4μ-in.) to a depth of a few mm.
- Solvents should have medium vapor pressure (100-300 mm Hg (2-6 psi)).
- Resin/solvent mix should have zero contact angle and low interfacial tension relative to calcium silicate hydrate (CSH) gel.
- Resin/solvent mix should have affinity for hydroxyl groups to form hydrogen bonds with CSH gel.
- Even some form of chemical bonding (condensation) such as occurs with silanes could have significant effect.
- Include surfactants that will assist displacement of surface moisture and associate with negative charges at the HCP interface to aid adhesion.

The second component of this system, "prime coat," also has sealer characteristics and is defined as a low viscosity resin <0.5 Pa-s (<500 cps) of the same generic type as the resin in the sealer-primer.

The responses to the questionnaires for this Synthesis revealed three different two-component combinations, as follows:

Sealer-Primer	Top Coat
Silane	Methyl Methacrylate
Epoxy: 50% solution in Xylene	Urethane
Epoxy: 50% solution in Xylene	Epoxy

There were two brands of the silane-methyl methacrylate system and one of each of the others.

One literature source defines a combination consisting of oligomeric alkylalkoxy siloxane primer and an acrylic top coat (*45*).

Another describes two different combination systems as follows (*46*):

- Special Coating for Bridge Decks
  - Primer: Oligomeric alkylalkoxy siloxane
  - Top Coat: Methyl methacrylate polymer
- Special Coating to Reduce Carbonation
  - Primer: Solution of organic silicone resin
  - Top Coat: Solution of oligomeric siloxane and acrylic resin (two coats).

Finally, Alberta Transportation and Utilities provides laboratory test data on the following dual systems (*47*):

Primer	Top Coat
Epoxy	Urethane (2 systems)
Epoxy	Epoxy
Silane	Methyl Methacrylate (3 systems)
Copolymer	Copolymer (2 systems)
Methyl Methacrylate	Methyl Methacrylate

PERTINENT SEALER PROPERTIES

Properties of sealers must relate primarily to the purposes for which the sealers are to be used (*48*). However, sealer properties should also be in concert with the conditions under which the sealer is used. Finally, economics and practicality require that sealer properties promote reasonable sealer cost, durability, safety, and applicability. Some typical properties of sealer products are summarized in Appendix B.

The purpose of using sealers is to retard, to the extent practical, the movement of liquid water, and dissolved ions that it contains (principally chloride), into concrete members. As described earlier, this can be done by either filling the pores near the surface, blocking their entrances at the surface with a barrier coat, or making the pore walls near the surface hydrophobic so that they repel water. Depending on which classification of sealing mechanism is employed, the sealer will have a different set of property requirements. Table 1 provides an assessment of the relative importance of 19 sealer properties (or effects) related to sealer durability, concrete protection, concrete performance, sealer application, economics, and aesthetics for the three classifications of concrete sealers. Most of the statements and relationships shown in Table 1 are self-evident. However, a few need explanation and/or further elaboration, which follows.

Sealer Penetration Depth

Penetration depth is a critical property for penetrating water-repellent and pore-blocking sealer types. Obviously, without adequate penetration, there is no sealing in these cases. In addition, on traffic surfaces penetration is essential for these types of sealers to assure adequate life span of the sealer and protection from UV radiation (*7,49*). Therefore, while Table 1 indicates that UV- and abrasion-resistance properties are unimportant for these sealer types, this is predicated on sufficient penetration to allow the concrete material to provide the needed protection to the sealer.

Penetration depth is one of the most controversial issues involved with sealers. Sealer consumers contend that manufacturers regularly overstate depth with reference to their products (*31,50*). Examination of product literature that accompanied completed questionnaires from sealer manufacturers, however, does not support this contention. Typical penetration depths in product literature for penetrating sealers range from 3 to 6 mm (0.125 to 0.25 in.), depending on sealer generic type and manufacturer (see Tables B-2 and B-3, Appendix B). By comparison, typical values from tests reported by users in the technical literature ranged from 2.5 to 6.4 mm (0.10 to 0.25 in.) for silanes (*7,18,27,30,33,51-55*), from 1.5 to 3.8 mm (0.06 to 0.15 in.) for siloxanes (*18,28,33,51-55*), and 1.3 to 3.0 mm (0.05 to 0.12 in.) for linseed oil (*8,50,56,57*). These typical ranges cover 50 to 60 percent of the reported values in each case. Values outside these ranges vary widely, both for manufacturers' product data and for users' test data. Therein lies the problem, for although the typical ranges for the manufacturers' data and users' test data are reasonably similar, the ranges are wide and outliers are common. The reason for this high level of variability lies in the factors that influence penetration depth. Sealer penetration depth is a function of molecular size, type and quantity of solvent, substrate permeability, moisture content of substrate, and surface preparation (*21*). For laboratory testing of a given sealer product, this boils down to substrate permeability and moisture content. Substrate moisture content is particularly critical (*21*). Because there is no universal standard test method for sealer penetration, there is little control within, and no uniformity between, testers regarding those two very important variables. The test methods reported for determining penetration depth range from examination of fractured or sawed face sections of treated specimens, using water (*27,30,51,52,58-62*), fluorescent dye (*50*), fugitive dye (*33,50*), phenolphthalein solution (*56*), acid etching (*56*), or infrared spectroscopy (*28*) for detection, to testing for water absorption after removal of successive thin layers of the treated surface (*7,63*). This matter will be explored further under Test Methods in Chapter 4.

Sealer penetration needs to be deep enough to provide adequate protection of the sealer against wear, weathering, and UV radiation, as previously noted. On the other hand, penetration that is too deep may diffuse the sealing ingredients to such an extent that poor waterproofing results (*63*). The lack of correlation sometimes observed between sealer penetration depth and performance (*50,56*) is probably due to a threshold effect with the critical depth being rather shallow. Nevertheless, penetration depth remains an important issue for the reasons cited. The desirable depth is about 6 mm (0.25 in.) with a minimum of about 3 mm (0.125 in.) (*17,21*). However, the regular attainment of these penetration depths will require not only proper selection of products, but also considerable care in surface preparation and assuring proper degree of concrete dryness. The quality of the concrete will also be a major factor in the penetration depth obtained. Penetration depths may be greater with poor quality concretes, which would require multiple applications to prevent diffusing the ingredients, while a 6 mm (0.25 in.) depth may not be possible with high quality concrete.

Ultraviolet (UV) Resistance

The importance of UV resistance for penetrating type sealers was discussed in conjunction with penetration depth in the previous section. For barrier coatings, UV resistance is obviously a critical

TABLE 1
IMPORTANCE OF SEALER PROPERTIES

Sealer Properties	Classification of Sealer[1,2] Water Repellent	Pore Blocker	Barrier Coating[3]
Related to Durability of Sealer			
a) Penetration Depth	C	C	NA
b) Ultraviolet Resistance[4]	U	U	C
c) Abrasion Resistance[5]	U[6]	U[6]	I
d) Reactivity with HCP Substrate	C	NA	NA
e) Weathering (other than UV)	U	U	I
f) Alkali Resistance	I	I	I
g) Bond Strength to Concrete	NA	NA	C
h) Flexibility	NA	NA	I
i) Service Life	I	I	I
Related to Protection of Concrete			
a) Chloride Absorption	I	I	I
b) Water Absorption	I	I	I
c) Water Vapor Transmission	I	S	S[7]
d) Crack Bridging	NA	NA	I
e) Deicer Scaling Resistance	I	I	I
Related to Performance of Concrete			
a) Surface Slipperiness (Skid Resist.)[5]	NA	NA[8]	C
Related to Sealer Use			
a) Ease of Application	I	I	I
b) Reapplicability	I	I	I
Related to Economics or Aesthetics			
a) Cost	I	I	I
b) Surface Appearance	NA	U	I

[1]Key: C = Critical, I = Important; S = Somewhat important; U = Unimportant; NA = does Not Apply
[2]Descriptions of Sealer Classifications:
Water Repellent—Penetrating sealer that renders the internal pore surfaces hydrophobic without blocking the pores to passage of gases and water vapor.
Pore Blocker—Penetrating sealer that blocks concrete pores reducing passage of liquids and gases with no visible surface coating.
Barrier Coating—Non-penetrating sealer that blocks concrete pores with a visible surface coating. Latex types allow higher levels of moisture vapor transmittance.
[3]Use caution when barrier coatings are applied in situations where vapor pressure may cause failure.
[4]Applies only to concrete exposed to direct sunlight.
[5]Applies only to traffic surfaces.
[6]However, abrasion resistance of the **concrete** is important.
[7]Much higher rates will be obtained with latexes. Use caution when barrier coatings are applied in situations where vapor pressure may cause failure.
[8]Except for a short period after application for some (e.g., linseed oil).

matter for surfaces exposed to direct sunlight. Some barrier coating materials, such as chlorinated rubber, must contain UV absorbers to provide adequate service life under direct sunlight exposure conditions. Epoxy, the most widely used barrier coating material for sealing concrete, is subject to chalking (which alters appearance) under UV exposure conditions, but the second most widely used barrier coating, acrylic, generally displays excellent resistance.

Reactivity of Concrete Substrate

Penetrating hydrophobic agents must react with the hardened portland cement paste in the concrete pore walls so that the organofunctional groups are properly oriented to carry out their water repelling task. The analogous property for barrier coatings is bond strength to the concrete. Penetrating, non-water-repellent pore blockers do not depend on any form of surface activity with the substrate other than wetability to promote uptake, but rather only on filling void volumes.

Service Life

Service life is the summation of effects of all the sealer properties related to durability. Service life is also one of the two primary ingredients (the other being cost) that dictate the economics of sealer use and selection. Further insight into service life of sealers will be covered in Chapter 3.

Chloride and Water Absorption

Resistance to the absorption of water and chlorides are the primary properties of water repellents, pore blockers, and barrier coatings relative to protection of concrete. Unless suitable performance is obtained regarding these properties, all other sealer properties are irrelevant.

Water Vapor Transmission

The ability of a concrete sealer to breathe (permit passage of water vapor) is especially important to penetrating water repellents where it promotes additional drying of the concrete, as previously described. It is of considerably less importance with pore blockers and barrier coatings except possibly in terms of releasing trapped moisture under unusual conditions and thereby preventing an adhesive failure due to vapor pressure. However, even these classes of sealers do, in general, breathe to some degree. The latex-type acrylic coatings, for example, are quite breathable. A minimum vapor transmission of 35 percent (relative to untreated concrete surfaces) is recommended (*17*).

Crack Bridging

Crack bridging is an important property of barrier coatings with regard to the protection afforded the concrete (*64*). Crack bridging is a function of flexibility, a physical property that also affects the durability of barrier coatings.

Deicer Scaling Resistance

Deicer scaling of concrete, a phenomenon related to freezing and thawing exacerbated by the use of deicing chemicals, initiated the practice of concrete sealing using linseed oil products in the 1930s (*40*). The role of concrete sealers to prevent or retard deicer scaling, especially of lower quality (higher water/cement ratio, lower entrained air content) concretes, continues.

DETERMINATION OF NEEDS

Preventing Reinforcement Corrosion

The use of concrete sealers constitutes an action to prevent deterioration. Therefore, its effectiveness and value increase with the condition level of the concrete at the time of application. In other words, sealers are most effective on new structures containing high quality (low W/C ratio, adequately air-entrained) concrete. However, from the economics point of view, the type and timing of sealer applications must also consider the degree of risk and costs involved. Degree of risk refers to those factors that contribute to the potential for concrete reinforcement corrosion: climate, exposure, traffic volume (which significantly affects deicer application rates), location (e.g., marine), and design details (e.g., open deck joints). The sealing of bridges should be done, according to one source, when the cost of sealing is less than the future cost of not sealing (*3*). It should be noted that discounted future costs should be used, in accordance with principles of engineering economic analysis.

While the protection received is maximized by sealing new structures in good condition, older and even deteriorating concrete bridge components may have longer service lives from sealing. Penetrating hydrophobic sealers, for example, can reduce reinforcement corrosion rates by increasing the resistivity of the concrete through the drying process that accompanies their use (*21*).

Preventing Other Forms of Deterioration

In addition to reinforcement corrosion considerations (the primary purpose for sealing concrete), it is necessary to take into account other deterioration related factors in determining the needs and requirements for sealing. For example, inadequately air-entrained concrete is subject to freezing and thawing deterioration. This form of degradation will not be stopped by any sealer in field applications, but it may be slowed down by the use of sealers. (However, there are concerns regarding the effect of penetrating water-repellent sealers on freezing and thawing durability of concrete—see Chapter 3). Other forms of deterioration that may be mitigated through use of sealers include carbonation, frost susceptible aggregates, deicer scaling, alkali-aggregate reaction, sulfate attack, acid attack, and dissolution.

Criteria for Concrete

The only criteria for concrete that have been set down to date relate to chloride-induced corrosion of reinforcing steel, which is the primary purpose for sealing concrete in highway applications.

TABLE 2
SUMMARY OF OKLAHOMA DOT SEALER POLICY (*65*)

Bridge Member	Chloride Exposure		
	High	Moderate	Low
Deck Slabs	Top of slab and underside of cantilever		None
Parapets	All Faces	Roadway Face	None
Approach Slabs	Top	None	None
Reinf. Conc. Bridges:			
- Major Grade Sep.	Top & Bottom of Slab	Top of Slab	None
- Other Locations	Top of Slab	Top of Slab	None
Box Culverts @ Grade	Driving Surface and Curbs		None
P.C. Beams:			
- Major Grade Sep.	All Exposed Faces of All Beams	End 5' of All Beams; Outside Faces & Btm. of Other Beams	None
- Other Locations	End 5' of All Beams; Outside Faces & Btm. of Other Beams		None
Post-Tens. Box Girders:			
- Top Slab	Top and Underside of Cantilever		
- Other	All Exterior Surfaces		
Pier Caps	Top, Sides, End		None
Abutments	All Exposed Areas of Bridge Seat & Front Face of Backwall		None
Columns	None	None	None
Wingwalls	None	None	None
Retaining Walls	None	None	None
Diaphragms	None	None	None

Most frequently, corrosion potential readings and chloride content determinations are used, but the limits and means of application vary. Recent work carried out under the Strategic Highway Research Program (SHRP) (*17*) specifies that sealers should not be applied to concrete bridge elements that display corrosion potential (half-cell) readings more negative than –250 mV and chloride contents equal or greater than 0.6 kg/m^3 (1.0 lb/cy) at the depth level of the shallowest 1 percent of the reinforcing steel. The Oklahoma Department of Transportation permits sealer use where chloride contents are less than 1.5 kg/m^3 (2.5 lb/cy) and the half-cell corrosion potentials are more positive than –350 mV CSE (*27*). In addition, Oklahoma specifies the bridge elements that may be treated depending on the anticipated deicing chemical exposure, which is defined in terms of traffic use (*65*). Bridges on urban expressways and interstate highways are defined as high deicer application, those on federal and state highway routes as moderate, and others as low. Table 2 summarizes the Oklahoma DOT policy. Alberta Transportation and Utilities (*66*) and the Department of Transport in Great Britain (*67,68*) employ dual requirements in much the same manner as Oklahoma DOT, but using different parameters. Both apply sealing to essentially the same list of bridge elements, as follows:

- Piers, columns, beams, and abutments within 8 m (26 ft) of the edge of the roadway;
- Piers, columns, beams, and abutments with a deck joint above, but with no provision for positive drainage;
- Bearing areas, ballast walls, and deck ends with a deck joint above;
- Deck beams and soffits directly over the roadway;
- Parts of wingwalls within 8 m (26 ft) of the edge of the roadway;
- Retaining walls within 8 m (26 ft) of the edge of the roadway;
- Curbs and parapets; and
- Concrete wearing surfaces.

Alberta, however, recommends that sealers be applied where 95 percent or more of the half-cell corrosion potential readings are more positive than −300 mV (CSE), with the exception that penetrating water-repellent sealers may be applied where corrosion is more advanced to slow down deterioration. The British Department of Transport requirements are much more complex. If bridges are less than 6 years old, sealers may be applied to the components previously listed. For bridges 6 years of age or older, those bridge elements with half-cell corrosion potentials more negative than −350 mV must be repaired. Those with corrosion potentials more positive than −350 mV will be treated; however, if their chloride content is in excess of 0.3 percent by weight of the cement (typically 1.2 kg/m^3 (2 lb/cy) of concrete), they will also have to be monitored.

SEALER USE BY CLASS OF SEALER

Sealer selection, by broad category, follows naturally from the information compiled and presented earlier on sealer properties and needs for sealers. The insights gained by virtue of the assessments of those data bases are summarized in Table 3, which provides general guidance for the selection of classifications of sealers to combat various forms of concrete deterioration. More specific recommendations, by generic sealer type, will be provided following the evaluation of sealer performance in Chapter 3.

TABLE 3
ESTIMATES OF SEALER USE, BY CLASSIFICATION, RELATIVE TO THE VARIOUS FORMS OF CONCRETE DETERIORATION*

Form of Deterioration	Delay Onset of Attack	Mitigate Attack in Progress
Reinforcement Corrosion	W, P, B	W
Freezing and Thawing:		
Low Entrained Air	P, B	N
Susceptible Aggregates	P, B	N
Deicer Scaling	W, P, B	N
Carbonation	P, B	P, B
Alkali-Aggregate Reaction	W	W
Sulfate Attack	W, P, B	W
Acid Attack (e.g., acid rain)	W, P, B	W, P, B
Dissolution (leaching)	W, P, B	W, P, B

Sealer Classification: W = Water-repellent penetrating sealer; P = Pore-blocking penetrating sealer; B = Barrier coating; N = None

*Based on synthesis of information presented in the following references: *3,7-9,11,14,17,20-22,27,28,30, 33,37,38,42,46,47,50,52,53,62,63,69.*

CHAPTER THREE

PRACTICE AND PERFORMANCE

SEALER PRACTICE

As part of the data acquisition process for this Synthesis, a questionnaire was mailed to each of the 50 state highway agencies plus the District of Columbia and to the 12 provincial highway agencies in Canada. Fifty-five of these agencies responded. The questionnaire form used with the highway agencies and summary tables detailing the responses are provided in Appendix A. Table 4 summarizes the generic types of sealers used (or approved for use) by the highway agencies.

A questionnaire was also mailed to sealer manufacturers in the United States. The questionnaire and detailed tables summarizing responses can be found in Appendix B. Detailed information was received on 62 sealer products, and combined with information from the technical literature and highway agencies, 409 concrete sealer products were compiled of which 273 were identified by generic type. The resulting breakdown by generic type is presented in Table 5.

The extent of use and applications of concrete sealers by high-

TABLE 4
GENERAL BREAKDOWN OF CONCRETE SEALER PRODUCTS BY GENERIC TYPE

Generic Type	Products Identified Number	Products Identified Percent
Penetrating Sealers (Water Repellents and Pore Blockers):		
Acrylic Sealers	40	17
Linseed Oil	9	4
Epoxy Sealers	62	27
Polyester	3	1
Silane	57	24
Siloxane	33	14
Silane/Siloxane Mix	6	3
Silicone	2	1
Silicate	11	5
Synthetic Gum Resins	4	2
Stearates	2	1
Urethane; Polyurethane	3	1
Total	232	100
Coatings and Undefined:		
Acrylic Coatings (HMWM* and modified thermoplastics)	11	27
Epoxy Coatings (incl. Nylon in Bisphenol Resin)	12	29
Cement Base Plus Latex Coatings	7	17
Two Component Deck Systems**	4	10
Chlorinated Rubber Coating	3	7
Fluoroelastomers (undefined)	3	7
Polymer (undefined)	1	3
Total	41	100
Grand Total	273	

*High molecular weight methacrylate.
**Penetrating sealer primer and coating material topcoat.

TABLE 5
GENERIC TYPES OF SEALERS USED (OR APPROVED FOR USE) BY HIGHWAY AGENCIES

Generic Sealer Type	Number of Departments of Transportation Using	Percent
Acrylic	9	5
Linseed Oil	16	9
Epoxy	26	15
Polyester	1	1
Silane	56	33
Siloxane	23	14
Silane/Siloxane Mix	4	2
Silicone	0	0
Silicate	5	3
Synthetic Gum Resins	17	10
Stearates	10	6
Urethane; Polyurethane	3	2
Total	170	100

TABLE 6
EXTENT OF USE OF CONCRETE SEALERS REPORTED BY HIGHWAY AGENCIES

Extent of Use	Number of Highway Agencies	Percent of Total
Extensive	17	29
Moderate	9	15
Limited	22	38
Experimental	5	9
None	5	9
Total	58	100

way agencies, as gauged by the questionnaire responses, are summarized in Tables 6 and 7, respectively.

SEALER PERFORMANCE

General

Performance is the most difficult issue to address pertaining to sealers. Laboratory and field evaluations of sealer performance characteristically show high variability not only among but within generic sealer groups (*39,54*). Considerable variability is often encountered even with tests of the same product under apparently similar conditions. Unquestionably, different sealer products, even of the same generic type, can be substantially different in their chemical and physical properties. It is also evident, however, that sealer performance is sensitive to environment, substrate, and application variables that, with interactions also considered, may be very extensive. In response to a query contained in the highway agency questionnaire, 42 percent of 50 respondents indicated having had problems with sealer performance (see Table A-5, Appendix A). According to respondents, this is the most serious problem area. Other problem areas polled were sealer selection (20 percent), sealer approval (27 percent), and sealer application (35 percent).

TABLE 7
APPLICATIONS OF CONCRETE SEALERS BY HIGHWAY AGENCIES

Applications	Number of Highway Agencies Using	% of Highway Agencies*
Decks	45	85
Beams	12	23
Piers, Caps	20	38
Parapets	28	53
Median Barriers	17	32
Abutments	27	51
Sidewalks	2	4
Curb and Gutter	4	8

*Of the 53 highway agencies reporting sealer use to some degree.

Laboratory Testing

An attempt was made to identify trends or tendencies existing within the mass of conflicting and confusing performance data found in technical literature and agency reports. Manufacturers data were excluded from this evaluation. By a wide margin, the bulk of the data uncovered pertains to laboratory, as opposed to field, testing. Data sets in which there exist a variety of generic types (each, preferably, containing a range of products) were sought out. These data sets were subdivided into classifications of types of test methods used. (The subject of test methods for sealers will be covered in Chapter 4.) The categories of testing methods used were:

- Absorption,
- Water vapor transmission,
- Chloride penetration,
- Freezing and thawing/deicer scaling,
- Reinforcement corrosion,
- Accelerated weathering, and
- Carbonation.

In all, 54 data subsets were identified from 17 reference sources. Each generic class of sealer represented in each test/method subset consisted of one or more sealer products. Sealers were ranked relative to performance in each test, weighted on the basis of the number of products in the generic class and on the number of data sets for that generic class/test method combination. The result is a rating from 0 to 100 in the direction of improving performance. Based on the ratings, the sealers were ranked under each test

TABLE 8
RANKING OF CONCRETE SEALERS BY VARIOUS TYPES OF LABORATORY TESTS*

	Absorption		Water Vapor Transmission		Chloride Penetration		F.-T./Deicer Scaling		Rebar Corrosion		Accelerated Weathering		Carbonation		Weighted Overall	
Generic Type	Rating	Rank	Rating	Rank	Rating	Rank	Rating	Rank	Rating	Rank	Rating	Rank	Rating	Rank	Rating	Rank
Silane	49	5	42	8	56	5	28	9	55	2	52	5	57	2	48	4
Siloxane	64	3	57	6	59	1	26	11	5	9	82	3	28	5	42	8
Epoxy	40	7	27	10	57	4	73	3	39	6	40	7	--	--	44	6
Gum Resin	45	6	57	6	46	7	33	8	72	1	9	10	71	3	50	2
Linseed Oil	17	11	23	11	40	8	77	2	25	7	91	1	--	--	33	11
Stearate	38	8	60	3	30	10	26	11	--	--	27	8	--	--	40	9
Acrylic	28	9	55	7	20	11	56	5	40	4	2	11	29	4	36	10
Silicate	5	12	58	4	9	12	33	8	0	10	82	3	--	--	22	12
Urethane	70	2	18	12	49	6	67	4	54	3	16	9	14	6	49	3
Chlorinated Rubber	54	4	31	9	57	4	54	6	39	6	--	--	--	--	47	5
Silicone	28	9	86	1	33	9	7	12	--	--	64	4	0	7	42	8
Dual Systems	76	1	73	2	58	2	92	1	11	8	46	6	86	1	62	1
No. of Data Sets Used	15		11		11		5		9		2		1		54	
References	*9,21,33,45, 47,69-77*		*9,21,33,47, 69-71,74*		*9,33,45,69, 74-77*		*49,71,72, 74,78*		*9,69,75, 76,79*		*9,71*		*45*			

*The calculated ratings (upon which the rankings are based) are weighted according to the numbers of products tested under each generic type of sealer. The overall ratings are also weighted according to the numbers of data sets used in evaluating each test method.

method (1 = top ranking). Finally, a weighted overall rating encompassing all of the test methods was calculated and a ranking was derived. The results are presented in Table 8.

Extreme care is recommended in interpreting the rankings presented in Table 8. First, the rankings represent average performances of the products and generic types in the various tests, and, as has been discussed, significant levels of variability are not uncommon here. Second, the laboratory tests themselves may bear little or no relationship to field performance. In other words, a generic class of sealer may have a very low ranking in one of the laboratory test methods, but a particular product within that generic class may actually have performed very well in the test. However, this is still no guarantee that it will perform well in the field. What is probably most important here is how the various generic types of sealers ranked over the range of tests, which is reflected in the overall ranking.

Correlations With Field Testing

Unfortunately, very little data were uncovered on controlled field testing in which a range of generic sealer types were evaluated under the same exposure and testing conditions. Two data sets in which chloride penetrations to the 1.3 to 2.5 cm (0.5 to 1.0 in.) depth range after 3 years of exposure under comparable climatic and environmental conditions were compiled. One set involves a series of reports covering various sealers tested by the Indiana DOT (*80-84*) during the late 1980s. The second involves a special study conducted by the Minnesota DOT during the same time frame (*85*). Rankings were compiled for these two data sets in the same manner as previously described for the laboratory tests. These rankings were then examined for correlation with rankings based on the laboratory test for chloride penetration (the test most nearly corresponding to the test used in the field) and on the laboratory overall rankings shown in Table 8. Correlation coefficients were calculated using Spearman's Rank Correlation Method (*86*). The rankings for the two field tests and for the comparable generic classes involved in the two laboratory tests are shown in Table 9. While only the correlation between the Indiana DOT data and the laboratory overall ranking is significant at the 95 percent confidence level, it is obvious that there are some striking similarities between the laboratory and field rankings. Notice, for example, that for both field tests the lowest ranked sealer classification corresponds to that of both laboratory rankings of the sealers tested. Also notice that the "dual system" (generally consisting of a silane primer and acrylic top coat) appears in the top spot in four of the six rankings, and is second and third in the other two. Given the

TABLE 9
COMPARISONS OF SEALER GENERIC CLASS RANKINGS: FIELD TESTS VERSUS LABORATORY TESTS*

	Rank		Laboratory Test Rankings (From Table 8) Chloride Penetration Test	Overall Ranking
Minnesota	1	Epoxy	Dual System*	Dual System*
DOT Field	2	Acrylic	Epoxy	Silane
Test	3	Dual System*	Silane	Epoxy
	4	Silane	Acrylic	Acrylic
	5	Silicate	Silicate	Silicate
Indiana	1	Dual System**	Siloxane	Dual System**
DOT Field	2	Gum Resin	Dual System**	Gum Resin
Test	3	Epoxy	Epoxy	Silane
	4	Siloxane	Silane	Epoxy
	5	Silane	Gum Resin	Siloxane
	6	Stearate	Stearate	Stearate

Spearman's Rank Correlation Coefficients

Field Tests	Lab Tests: Chloride Penetration	Lab Tests: Overall
Minnesota DOT	+0.500	+0.200
Indiana DOT	+0.429	+0.829***

*Rankings by generic class.
**Penetrating sealer (commonly silane) primer plus topcoat (commonly methyl methacrylate).
***Correlation coefficient significant at 95% level.

high variability involved in sealer performance and the relatively small amount of data available to formulate the ranking (especially field), the correspondence between the lab and field rankings is really quite remarkable.

Commentary on Sealer Rankings

It is important at this point to note factors that affect the performances of sealers in certain laboratory tests and how these factors may influence the rankings shown in Tables 8 and 9. Likewise, the field performance of some generic classes of sealers are unduly influenced by certain substrate, environment, or material factors. In order to promote a better understanding of the rankings shown in Tables 8 and 9 and the considerations that should be involved in their interpretations, these factors will be briefly discussed in the paragraphs that follow.

Silane and Siloxane

The organosilicon sealers (principally silane and siloxane) are subject to wide variations in performance in field testing. Indeed, the rather mediocre rankings for the silanes in the two field tests shown in Table 9 result from this factor. In both cases, several silane products were tested and the performances ranged from the best to the worst relative to all of the products of all generic classes of sealers tested. Others have had similar experiences with silane (*39*). Recall that the rankings are based on mean performance values for all of the products in each generic classification. This may explain in part why reports of unsatisfactory performance from highway agencies are common for silanes and siloxanes (*28,62,87-93*). The primary reason for the highly variable performance behavior of these sealers is likely misapplication in their use. It will be recalled from the discussions in Chapter 1 that silane requires the presence of normal alkalinity of the hydrated cement paste in the concrete substrate and moisture to produce the hydrolysis and condensation reactions that create the hydrophobic pore surfaces. Thus, older and higher porosity (higher water/cement ratio) concrete, subject to higher levels of carbonation, may not develop a sufficient zone of water repellency at the concrete surface (*7,49,54,94*). Notice that the greater the depth of carbonation the longer it takes for the volatile silane to penetrate to a depth at which it can react. Notice also that higher water/cement ratio concretes with their higher porosities have increased pore surface area per unit volume of substrate and higher permeability. These factors dilute the effect of the sealer by allowing deeper penetration into substrates that contain more internal surface area to cover. It is because of the aforementioned factors that the performance of silanes has been shown to improve markedly with the use of decreasing quantities of the carrier, or solvent (*31,32*). The use of silane without the carrier (i.e., essentially 100 percent active ingredient) has even been recommended (*3,7,53*).

As mentioned, some moisture must be present to initiate the hydrolysis reaction with silanes and siloxanes. However, if the concrete is saturated at the time of application, the only way that the sealer can penetrate the pores is by diffusion, which is an exceedingly slow process that allows the sealer to be lost by evaporation, runoff, or flushing by rain (*21*). Therefore, the concrete should be dry when these types of sealers are applied. Tests indicate that at least 48 hours of air drying is required (*21*). Immediate post-sealer application misting with water should be used to assure the presence of sufficient moisture for the hydrolysis reaction (*27*). In summary, silanes (especially, because of their high volatility) and siloxanes work best when applied to dry, relatively new, high quality, low permeability (low water/cement ratio) concrete. Lower quality concretes may be more effectively sealed by barrier coatings (*32*) or pore blockers.

Rankings based on laboratory testing showed that silanes and siloxanes characteristically perform poorly in laboratory testing for freezing and thawing or deicer scaling resistance (*95-98*). This is true of the entire class of water-repellent-type sealers (including stearates and silicones), as shown in Table 8. However, no evidence that this effect carries over into the field was found in the literature. One explanation is that the concrete in laboratory freezing and thawing or deicer scaling testing is not afforded the chance to dry out, and the hydrophobic surfaces of the pore walls provide sufficient resistance to the flow of water ahead of the advancing frost zone to produce destructive pressures within the concrete (*96*). Thus, the laboratory freezing and thawing test rankings, and consequently overall laboratory test rankings, of these materials should probably be higher than indicated in Table 8.

Barrier Coating/Pore-Blocking Sealers

The properties of those generic classes of sealers that can function as either pore blockers or barrier coatings (as defined in Chapter 2), depending on the amount of diluent that they contain, tend to vary with solids content. This includes epoxies, acrylics, urethanes, and chlorinated rubbers. Statistical analyses of data on epoxies, acrylics, and urethanes, extracted from the U.S. Army Corps of Engineers "REMR Material Data Sheets" (*70*), reveal that inverse correlations, significant at better than 95 percent, exist between solids content and water absorption for epoxies, urethanes, and water vapor transmission for epoxies. Further, the effects can be significant. On average, reducing the solids content of epoxies from 100 to 20 percent increases water absorption from essentially nil to about 67 percent of control. Over the same range of solids contents, water vapor transmission increases, on average, from nil to approximately 26 percent of control. However, the relationships are nonlinear so that the water absorption and water vapor transmission rates at a 50 percent solids content average only about 7.5 and 3 percent of control, respectively. The acrylics do not display significant correlations between percent solids and water absorption or water vapor transmission (although the trends are perceptible). This is probably an anomaly created by the complicating factor of an excessively large polymerization shrinkage factor for acrylics (up to 21 percent for polymethyl methacrylate).

Linseed Oil

As shown in Table 8, linseed oil generally displays very poor performance in laboratory testing except for freezing and thawing/deicer scaling (*50*) and accelerated weathering tests. However, linseed oil—one of the oldest sealer materials for concrete—has a long record of apparently satisfactory field performance (*8,19,57,99-103*). Even though the use of linseed oil has declined somewhat in recent years (*2*), it is still approved by about one-quarter of the highway agencies that use sealers. About one-sixth of the agencies that allow sealers specify it exclusively (see Table A-1, Appendix A). In side-by-side field testing in Vermont in 1987, linseed oil reportedly outperformed silane (*93*) and mineral gum (*104*) sealers. In comparison field testing in Pennsylvania in 1989, linseed oil outperformed a sodium silicate, a solvent dispersed epoxy, a water dispersed epoxy, one of two resins in mineral spirits, and a high molecular weight methacrylate sealer (*105*). Only one of the resin-in-mineral-spirits sealers possibly performed better. Linseed oil was found to be very effective in reducing chloride intrusion in the Federal Highway Administration's landmark "time to corrosion" studies (*106*). The general consensus appears to be that linseed oil is an inexpensive concrete sealer that has demonstrated effectiveness in combatting deicer scaling of marginal quality concretes. Its primary drawback is the acknowledged fact of a relatively short period of effectiveness before reapplication is needed — estimated between 1 and 5 years, commonly 2 (*8,19,37,69,89,106-109*). That drawback is usually considered to be more than offset by the low cost of the material.

Given the level of acceptance of the material, apparently based on a long history of acceptable field performance, the question of the veracity of the typically poor laboratory test results comes to the fore. The technical literature reveals strong evidence that the laboratory test methods are generally not appropriate for testing linseed oil. The problem is that linseed oil, a so-called "drying oil," hardens by oxidative polymerization. This can be a relatively slow process, especially when the linseed oil is held within concrete pores where the oxygen necessary to promote polymerization must be transported by diffusion. Furthermore, before it hardens, linseed oil reacts with free lime and alkalies in the hardened cement paste in saponification reactions, temporarily softening the concrete surface (as previously discussed in Chapter 2). It is believed that the poor performance in laboratory testing occurs because that testing normally takes place before the linseed oil has polymerized and the penetrated zone has stabilized. Observations from three independent studies are cited as evidence for this explanation. In the often quoted NCHRP Report 244 on concrete sealers for bridges, the investigators observed that specimens treated with linseed oil that had been subjected to 5,000 watt hours/m^2 (465 watt hr/ft^2) of UV radiation prior to chloride penetration and water absorption tests far out-performed specimens that had not been exposed to the radiation (*9*). A virtually identical situation occurred in sealer testing carried out at the U.S. Army Corps of Engineers Waterways Experiment Station (*71,110*) where accelerated weathering tests (shown in Table 8) involving the use of UV exposure produced results similar to those reported in NCHRP Report 244.

In the third event, concrete was deeply impregnated with linseed oil by oven drying and vacuum saturating concrete test cylinders with 50/50 boiled linseed oil/mineral spirits (*111*). The cylinders were subjected to compressive strength testing, along with companion, unimpregnated specimens, at various time intervals up to 120 days. A marked strength reduction of about 15 percent occurred immediately. However, the impregnated concrete recovered the lost strength in less than 2 weeks and continued to gain strength with time. All three cases demonstrate the delayed effects of polymerization of the linseed oil. Therefore, the low rankings of linseed oil in laboratory testing for absorption, water vapor transmission, and chloride penetration may not be warranted.

Silicates

A problem may exist with laboratory testing of silicates akin to that encountered with linseed oil. Recall from the discussion of silicates in Chapter 2 that the protective mechanism involved appears to be pore blocking, having evolved from a possible variety of reactions that involve imbibition of, and reaction with, water. The parallel with the linseed oil situation is obvious, and it would be expected that silicates would fare poorly in water absorption and chloride penetration testing. This suspicion is reinforced in the accelerated weathering testing where ample reaction time occurs and silicates, like linseed oil, do very well (see Table 8). However, unlike linseed oil, silicates have not done well in the field and in general, have given mixed (*112*) or poor (*85*) results.

Dual Systems

Dual systems consist of a penetrating primer (either a water repellent or a pore blocker) with a pore blocker or barrier coating top coat. The most commonly used type consists of an alkylalkoxy silane primer and a polymethylmethacrylate top coat. The number one ranking for this generic category in the laboratory tests agrees with the field test results (see Tables 8 and 9). Considering the rankings of the components of dual systems, it appears that there are powerful synergistic effects at work. This may occur, for example, by virtue of the combined ability of silane to repel moisture and the acrylic to enter and block pores while still providing a measure of vapor transmittance because of the shrinkage upon polymerization. Also, the acrylic will significantly combat effects of surface wear. As noted above, there are reasons to suspect that the laboratory test rankings for silane and acrylic separately may be too low. Therefore, the level of synergism required to produce the performance level for the dual system indicated in Tables 8 and 9 may not be as great as first indicated.

Gum Resins

In Chapter 2 it was observed that gum resins, along with mineral gums, turned out to be a third place finisher (behind the organosilicons and epoxies) as a generic category of choice by highway agencies (see Table A-1, Appendix A). This rating was based on the number of products approved for use and not on actual quantity used. A high level of satisfaction exists, however, and is supported by the laboratory and field test rankings as well (see Tables 8 and 9).

Silicones

Silicones, the earliest of the water-repellent concrete sealers, have not, in general, fared well in laboratory or field applications (*101,113,114*). They are rarely used by highway agencies as concrete sealers today.

SEALER TYPE SELECTION

The specific choice of sealer type for a given service should evolve from a life-cycle cost analysis of the candidate sealer types that are suitable for that service. This section deals with the selection of sealer type candidates as a function of the field exposure parameters. Life-cycle costing to select the specific sealer from the group of candidates requires knowledge of the service lives and costs of the candidate sealers. Those factors are covered later in this chapter and in Chapter 5, respectively.

Sealer Groupings

Taking into account the synthesis of information derived from the literature searches and questionnaire responses, as documented to this point, the generic types of sealers deemed to be suitable for use in highway applications were identified. By sealer class they are:

- Water repellents:
  - Alkylalkoxy silane
  - Oligomeric alkylalkoxy siloxane
- Pore blockers:
  - Gum resin in solvent
  - Boiled linseed oil in solvent
- Pore blockers or barrier coatings (depending on the amount of dispersant used):
  - Epoxy resin
  - Urethane
  - Acrylic
  - Chlorinated rubber
- Dual System (combination water repellent and pore blocker):
  - Alkylalkoxy silane primer/acrylic top coat.

The selected generic sealer types were then divided into five groups according to common sealer class and performance level, as follows:

Group	Generic Types
A	Silane; Siloxane
B	Epoxy; Urethane
C	Acrylic; Chlorinated Rubber
D	Gum Resin; Linseed Oil
E	Dual System (silane primer/acrylic top coat)

Field Exposure Parameters

Concrete Substrate Conditions

Two concrete substrate considerations are important relative to the performance of silane and siloxane. As previously discussed,

TABLE 10
LEVELS OF SEALER SERVICE

Level of Service	Types of Highway Facility Members
Severe	Bridge Decks; Pavements
Moderately Severe	Bridge Sidewalks, Curbs, Parapets, Piers, Columns, and Pier Caps; Median Barriers, Culvert Headwalls, Catch Basins
Moderate	Bridge Beams*, Soffits, Facia, Diaphragms*, Pedestals*, Backwalls*, Abutments*, and Wingwalls; Roadway Retaining Walls; Sound Barrier Walls

*Moderately severe service if open or leaking deck joints exist.

they are depth of carbonation and capillary porosity. The degree of carbonation is a function of the age of the concrete and the water/cement ratio. Capillary porosity is predominantly a function of water/cement ratio, but is also influenced by curing. A water/cement ratio of 0.45 was selected as the breakpoint between low and high values. The age of one year was selected as the breakpoint between young and old concrete relative to carbonation. This is based on a relationship proposed by Sommerville (*115*):

$$t = [0.40 - 0.5\ (w/c)]d^2$$

where:

t = time in years
w/c = water/cement ratio by weight
d = depth of carbonation, mm

Because silane and siloxane are adversely affected by carbonation (as previously discussed), the penetration depths of these materials relative to carbonation depth is a matter of some importance. As discussed in Chapter 2, typical penetration depths are 2.5 to 6.4 mm (0.10 to 0.25 in.) for silanes and 1.5 to 3.8 mm (0.06 to 0.15 in.) for siloxanes. Therefore, carbonation depths should be no more than about 2.5 mm (0.10 in.) when using these sealers. Thus,

$$t = [0.40 - (0.5)(0.45)](2.5)^2 = 1 \text{ yr. (approx.)},$$

and silanes or siloxanes should not be applied to concrete greater than one year old (unless the carbonated surface is removed).

Concrete Member/Service

Three levels of severity of service, in terms of the locations of sealer applications on highway structures, were formulated. "Severe" service refers to surfaces subject to traffic wear as well as direct application of deicing chemicals. "Moderately severe" service pertains to members subject to splashing or spraying of brine by traffic, or drainage of deicer melt water through open deck joints. "Moderate" service relates to areas generally protected from direct deicer application or generally out of the range of direct traffic splash, but occasionally subject to runoff and/or aerosols containing deicing salts. Table 10 summarizes the three levels of sealer service and the type of highway facility members involved.

Environment

Environment refers to the extent of time that the subject highway member remains in a saturated condition. Consideration of this factor is necessary, given the questionable performance of the organosilicon sealers under saturated freezing and thawing conditions. Also, gum resins have displayed marginal freezing and thawing resistance in the laboratory (see Table 8). Two categories of environment are used: (1) frequently to continually wet and (2) dry to intermittently wet. Notice that the level of chloride contamination is not addressed here. It enters the sealer selection process through its effect on service life, which is discussed later.

Recoating

The general guidelines for the selection of sealers in reapplication procedures are as follows:

- Silanes or siloxanes may be reapplied over existing silane- or siloxane-sealed surfaces, but not over surfaces that have been sealed with other generic types of sealers. This is because silanes and siloxanes must react with the concrete substrate to be effective, and the vestiges of previous sealers would interfere.
- Linseed oil and gum resin may be reapplied over former applications of the same materials (including each other) and over former silane- or siloxane-coated surfaces. However, they should not be applied over epoxy-, urethane-, acrylic-, or chlorinated rubber-coated surfaces. The latter sealers will block pore openings preventing penetration by linseed oil or gum resins while silanes and siloxanes will not.
- Manufacturer's recommendations must be followed concerning the recoatability of barrier coating-type materials. In general, epoxies and urethanes recoat themselves poorly, while chlorinated rubber recoats itself well (*37*). Acrylics also usually recoat themselves acceptably.

Sealer Selection

The selection matrix, based on the principles and factors defined in the immediately preceding paragraphs, is presented in Table 11. It must be reiterated here that generic type is not a guarantee of individual sealer performance. Broad ranges of performance of the individual products within each generic type is often the norm.

TABLE 11
SEALER CANDIDATE SELECTION MATRIX

Group	Sealer Types	Sealer Class[b]	Concrete Substrate Conditions[a] — Age: <1 year	Age: >1 year	Water/Cement Ratio: <0.45	Water/Cement Ratio: >0.45	Service: Severe	Service: Moderately Severe[c]	Service: Moderate	Environment[d]: Wet	Environment[d]: Dry	Moisture Recoating Application (Group May Recoat:)[e] A	B	C	D	E
A	Silane Siloxane	WR	X	X[f]	X		X	X			X	X				
B	Epoxy Urethane	PB or BC[g]	X	X	X	X	X	X	X	X	X	X			X	
C	Acrylic Chlorinated Rubber	PB or BC[g]	X	X	X	X		X	X		X	X		X[h]	X	X[i]
D	Gum Resin Linseed Oil	PB	X	X	X	X		X	X	X[j]	X	X			X	
E	Dual System[k]	WR & PB	X	X[f]	X		X			X	X	X				

Notes: [a]Initial application.
[b]WR = water repellent; PB = pore blocker; BC = barrier coat.
[c]Also applies to "Moderate" service condition where open or leaking deck joints exist.
[d]"Wet" = frequently to continually wet; "Dry" = dry to intermittently wet.
[e]For example, Group B may recoat Groups A and D, but not Groups B, C, and E.
[f]If carbonated surface is removed.
[g]Depends on quantity of diluent used.
[h]Reapplication in-kind.
[i]Acrylic only.
[j]Linseed oil only.
[k]Silane primer plus acrylic top coat.

Sealer testing (covered in Chapter 4) must be carried out to identify products meeting required performance standards.

SEALER SERVICE LIFE

It is assumed here that the primary purpose for sealing concrete is to delay the onset of reinforcement corrosion by retarding the influx of chloride ions. For those instances where the purpose is to retard freezing and thawing or deicer scaling deterioration of marginal quality concrete, boiled linseed oil/solvent mixtures should be used, and the service life of this treatment is usually considered to be about 2 years (as previously discussed).

The service life of a concrete sealer relative to chloride ingress is a function of three categories of factors: (1) sealer material properties, (2) service conditions related to sealer durability, and (3) chloride diffusion related factors.

Sealer material properties are those characteristics that collectively dictate the relative performance of sealer products in side-by-side laboratory testing. This assumes, of course, that the factors contained in the other two categories are held constant during the testing procedures. Service conditions related to sealer durability—such as UV light or abrasion by traffic, ice, wind, or water—may also be evaluated in laboratory testing. This is usually done in tests subsequent to the basic sealing effectiveness testing. Because the transmittance of chloride ions needed to initiate reinforcement corrosion is a diffusion process, most of the factors pertinent to concrete sealer life are embodied in the physical laws governing that mechanism of mass transport. They are defined in the following mathematical relationship, which is a standard solution of the partial differential equation representing Fick's Second Law of Diffusion:

$$C_{(x,t)} = C_o\left[1 - \mathrm{erf}\left(\frac{x}{2\sqrt{D_c t}}\right)\right]$$

where:

$C_{(x,t)}$ = chloride concentration at depth x after time t for an equilibrium chloride concentration C_o at the surface
erf = error function (from standard mathematical tables)
D_c = the diffusion constant

The factors included in this third category are manifold. The diffusion constant is influenced by concrete quality (water/cement ratio) and climate (mean temperature). The equilibrium chloride concentration is a manifestation of the severity of chloride exposure of the concrete member. At the time of corrosion initiation, $C_{(x,t)}$ represents the critical, or corrosion threshold, chloride ion concentration at the level of reinforcement. At the same time, x represents reinforcement cover, and t the length of the protection period of the system.

With a sealer in place, the diffusion process defined above involves chloride ions that have breached the sealer. Obviously, if the sealer is totally impervious to penetration by chlorides over the useful life of the structure, no diffusion of chloride ions into the concrete occurs. However, all sealers are permeable to chlorides to

TABLE 12
CALCULATED SEALER SERVICE LIVES FOR THE RANGE OF CONDITIONS ASSOCIATED WITH HIGHWAY STRUCTURES IN THE U.S. (*13,116*)

Position	Diffusion Constant, D_c(cm^2/yr)	Equilibrium Chloride Concentration, C_o (kg/m^3)	Calculated Sealer Service Life (years) Silane	Siloxane	Water-Borne Epoxy	Solvent-Borne Epoxy
Horizontal	0.84	8.9	0.5	0.9	--	--
Horizontal	0.32	2.4	10.0*	10.0*	--	--
Vertical	0.84	8.9	0.2	0.1	negligible	negligible
Vertical	0.32	2.4	10.0*	10.0*	7.3	5.0

*Maximum life = 10 yr (8 yr for bridge decks).

some degree. This has been termed the "leakage factor" in recent work on sealer service life determination (*13,17,116*), and is essentially represented by chloride penetration testing in the laboratory (i.e., the first category, sealer material properties). It is reasoned that the increment of leakage provided by each reapplication over the life of the structure is constant and that the sum of reapplications produces the equilibrium chloride content beneath the sealer. This chloride content is just sufficient to result in the critical corrosion threshold chloride concentration at the reinforcement at the end of the useful life of the structure. Consequently, the total number of sealer applications over the life of the structure and the service life of one sealer application are fixed. An example showing the details of this procedure is presented in Appendix C. Table 12 presents the range of service lives determined by this method for the range of chloride exposures (C_o) and diffusion constants (D_c) representing highway conditions and practices in the United States (*13,116*). Table 13 presents the range of equilibrium chloride content (C_o) and mean diffusion constant (D_c) values for 10 states representing the ranges of values for the United States (*17*). The reason that the service lives are not the same in Table 12 for constant C_o and D_c values of 8.9 kg/m^3 (15 lb/yd^3) and 0.84 cm^2/yr (0.13 in.^{2}/yr), respectively, is because the horizontal and vertical positions have different leakage factors. The diffusion equation is only one component of service life determination. The same is true at the lower values of C_o and D_c, but the results are masked by truncation of service life at 10 years. See previously cited example calculation in Appendix C.

Another approach to the problem of service life of concrete sealers involves measuring the slope of chloride content plotted against numbers of weathering cycles on laboratory test specimens with and without sealers (*33,63*). The number of weathering cycles at which the slope for a sealed specimen equals that of the nonsealed control specimen represents the service life of the sealer. The weathering cycles consist of cycles of UV exposure, wetting and drying with 15 percent salt solutions, and temperature variations between 0 and 73°F (−17.8 and 22.8°C). In practice, chloride determinations are made only every 50 cycles and the actual end point is interpolated. This procedure is less quantitative in terms of actual field service life than the first one, but is also much simpler to carry out.

TABLE 13
RANGE OF EQUILIBRIUM CHLORIDE CONTENT (C_O) AND MEAN DIFFUSION CONSTANT (D_C) FOR 10 STATES (*17*)

State	Range of Equil. Chloride Content C_o(kg/m^3)	Mean Diffusion Constant D_c(cm^2/yr)
California	0.0 - 2.3	1.61
Delaware	4.7 - 5.8	0.32
Florida	2.4 - 4.6	2.13
Indiana	4.7 - 5.8	0.58
Iowa	4.7 - 5.8	0.32
Kansas	0.0 - 2.3	0.77
Minnesota	2.4 - 4.6	0.32
New York	5.9 - 8.8	0.84
West Virginia	4.7 - 5.8	0.45
Wisconsin	5.9 - 8.8	0.71

It is necessary to reemphasize that sealer life is an important variable in the sealer selection process. Without reasonably good indications of prospective sealer service lives for given needs, it is simply not possible to make a rational choice of a sealer from prospective candidates using life-cycle cost analysis. It is possible to compile mean service lives for generic types of sealers by using empirical data. However, these data will not only be subject to wide variations due to product variations within the generic types (as discussed relative to sealer performance), but also by the range of variables that particularly affect service life, covered earlier in this section and illustrated in Table 12. For completeness and comparison purposes, service life data compiled from the literature search for this Synthesis are presented in Table 14.

TABLE 14
SUMMARY OF SEALER SERVICE LIFE DATA FROM THE TECHNICAL LITERATURE

Generic Type	Conditions	Service Life (years)	Reference(s)
Silanes/Siloxanes	Bridge Decks: high traffic volumes	4 - 8	*33,39,116*
	" " : general (better sealers)	>10	*63*
	Piers, Pier Caps, Beams: subject to abrasion	<10	*116*
	" " " " : light-moderate exp.	6 - 8.5	*33*
	" " " " : vertical surfaces	indefinitely	*63*
	General	5 - 7	*17*
Epoxies	Penetrants (<50% solids) - General	<2 - 10	*39,63*
	" (" ") - Wave or ice action	1 - 3	*17*
	" (" ") - No " " " "	<1	*17*
	Coatings: moderate exposure conditions	7 - 8	*33*
	" : light exposure conditions	<10	*33*
	" : sea spray and splash	6 - 10	*17*
	" : deicer runoff	10 - 14	*17*
	" : abrasive wear conditions	<1	*116*
	" : general	10 - 15	*63*
Urethanes	Coatings: sea spray and splash	10 - 14	*17*
	" : deicer runoff	14 - 18	*17*
	" : general	10 - 15	*63*
Acrylics	Coatings: moderate exposure conditions	5 - 7	*33,39*
	" : light exposure conditions	7	*33*
	" : sea spray and splash	9 - 13	*17*
	" : deicer runoff	13 - 17	*17*
	" : general	10 to >15	*18,63*
Boiled Linseed Oil	Not exposed to wave or ice action	1 - 3	*17*
	Exposed to wave or ice action	<1	*17*
	General	1 - 5 (avg. 2)	*8,19,37,69, 89,106,108,109*
Dual Systems	General	>15	*18*
Sealers - General	Bridge Deck Sealers	7 (avg.)	*117*
	" " " : median*	4 - 5	*12*
	" " " : mode*	5	*12*
	" " " : range*	1 - 25	*12*
	" " " : interquartile range*	2 - 10	*12*
	" " " : mean*	16.5	*11*
	" " " : range*	10 - 25	*11*
	" " " : mean from lit.	5	*11*
	Non-Deck - Cl runoff or spray: median*	5 - 10	*12*
	" " " " " : mode*	10	*12*
	" " " " " : range*	2 - 25+**	*12*
	" " " " " : interquartile range*	3 - 10	*12*

*Questionnaire Data
**Chloride spray: 2 - 35

CHAPTER FOUR

SEALER PRODUCT EVALUATION AND TESTING

TESTING REQUIREMENTS

For rational and effective use of concrete sealers, product testing and evaluation requirements should be fulfilled with respect to four areas: (1) product qualification, (2) product quality assurance, (3) field application quality assurance, and (4) field testing for assessment of sealer reapplication needs and product performance.

Product qualification testing is intended to identify the products that meet the requirements relative to specific applications. As demonstrated in Chapter 3, wide ranges of performance are commonplace among products within generic classifications relative to specific service requirement criteria. Given the extensive variety of products available and the changes and variations in product lines that characterize the concrete sealer market, most of the testing is carried out in this area.

Product quality assurance tests are needed to assure the user that the quality of the product has not changed deleteriously since product qualification testing. This area also may include testing to detect quality degradation during storage.

Field application quality assurance refers to testing carried out prior to and during the application of sealers to assure that they have been properly installed on appropriately prepared concrete substrates.

Finally, field testing for assessment of sealer reapplication needs and product performance is intended to assure the integrity of the concrete through proper maintenance of the sealer system.

CURRENT PRACTICE

A large number of test procedures have been used with concrete sealers. Table 15 presents a compilation of those that were identified in the literature search and questionnaire surveys conducted for this synthesis, and although extensive, it certainly is not all-inclusive. Of the nearly 100 test methods listed in Table 15, fewer than 20 were developed specifically for use with concrete sealers. With regard to this, questions will likely arise concerning the relevance of the tests to sealers, if not the accuracy of the results.

The questionnaire survey conducted among highway agencies (Appendix A) indicates that most (57 percent) of the agencies that reported using sealers depend, at least partially, on internal testing procedures for sealer qualification (see Table 16). The most popular types of sealer evaluation and acceptance tests used are chloride ion penetration, absorption, and water vapor permeability at 49 percent, 43 percent, and 32 percent, respectively (see Table 17). The survey reveals, however, that fewer than one-third of the highway agencies that reported using sealers do any form of field performance testing of them (see Table 18).

SEALER PRODUCT DATA BASES

Because of the large number of concrete sealer products and the time and expense of evaluation and acceptance testing, the use of a national data base of acceptable materials, to avoid duplication of effort, is an attractive concept. Such a data base does exist in the AASHTO-FHWA "Special Product Evaluation List" (SPEL). The input to SPEL is provided by state highway materials engineers and by the FHWA as an activity of the AASHTO Subcommittee on Materials. The June 1991 edition of SPEL (*182*) lists 275 proprietary concrete sealer products by name under the following ratings:

Rating	Number of Sealer Products
Approved	87 (31.6%)
Not Approved	67 (24.4%)
Pending Approval	119 (43.3%)
Not Documented	2 (0.7%)

The difficulty with the SPEL data is the diversity of the information sources. As already observed, a wide range of testing procedures is used for acceptance testing (not to mention acceptance criteria). Also, the needs and applicability of testing vary geographically.

The most comprehensive single-agency sealer product data base uncovered in the research for this Synthesis is the one compiled by the U.S. Army Corps of Engineers under the Repair-Evaluation-Maintenance-Rehabilitation (REMR) program at the Waterways Experiment Station in Vicksburg, Mississippi. The data base can be accessed by telecommunication through the "Corps of Engineers Repair Products Data Base For Concrete and Steel Structures" (*183*). This data base is menu driven and has help windows to facilitate its use. There is no cost to users, except the long-distance telephone call. The major advantages of the REMR data over SPEL are the involvement of only one agency (Corps of Engineers) in testing and the fact that quantitative test data are provided (as opposed to qualitative pass/fail indications). For more detailed information regarding the REMR data base, see the Glossary of Terms at the end of this Synthesis.

Some individual highway agencies, most notably Alberta Transportation and Utilities, have extensive sealer product testing data banks.

TESTING NEEDS

As observed at the beginning of this chapter, sealer testing should include product qualification, product quality assurance, field application quality assurance, and testing for reapplication needs and product field performance. Presently, only the first of these is generally addressed. Furthermore, the relevancy of the majority of the tests presently used for product qualification is questionable and these tests are largely responsible for the diverse apparent performance of given products by different agencies. As a final point, the management of sealer use and selection of sealer

TABLE 15
TESTING PROCEDURES THAT HAVE BEEN USED IN CONJUNCTION WITH SEALERS

Description	Test Method*	References
A. Sealer Characterization Tests		
Percent Solids	ASTM D1259	*118*
	ASTM D5095	*119*
	Alberta T & U B390	*120*
	and BT003	*121*
	LADTD DOTD 244	*28*
	US Army COE	*71*
Percent Volatiles	ASTM D2369	*122*
Spectroanalysis	Alberta T & U B388	*123*
	LADTD DOTD 610	*28*
Viscosity	ASTM D1824	*124*
Specific Gravity	LADTD	*28*
pH	LADTD	*28*
Coatings:		
Bond to Concrete	ASTM C882	*125*
	ASTM D4541	*126*
Tensile Strength and Elongation	ASTM D638	*127*
Shrinkage	ASTM C883	*128*
B. Concrete Property Tests Relevant to Sealer Applications		
Surface Condition	ACI 515.1R	*34*
Moisture Condition	AASHTO T239	*129*
	ASTM D3017	*130*
C. Sealer Qualification Tests		
Water Absorption	AASHTO T32	*131*
	ASTM C67	*132*
	ASTM C97	*133*
	ASTM C140	*134*
	ASTM C642	*135*
	Alberta T & U B390	*120*
	and BT001	*136*
	NCHRP 244; Ser.I, II, III	*9*
	NYDOT 717-1E	*137*
	OKDOT OHD L-39	*138*
	RIDOT	*139*
	US Army COE Inverted Funnel	*71*
	VAT VT-AOT-MD-12	*22,140, 141,142*

*See Glossary of Terms and Acronyms.

TABLE 15
TESTING PROCEDURES THAT HAVE BEEN USED IN CONJUNCTION WITH SEALERS
(Continued)

Description	Test Method*	References
Chloride Penetration	AASHTO T259	*143*
	MIDOT	*144*
	NCHRP 244; Ser. I, II, III, IV	*9*
	NHDOT	*145*
	NJDOT	*146*
	NYDOT 717-1E	*137*
	RIDOT	*139*
	SHRP C-103	*17*
	VAT VT-AOT-MRD-7-85	*141,147*
	AASHTO T277	*178*
Sampling for Chlorides	AASHTO T260	*148*
	PADOT PTM 414	*149*
	SHRP C-101	*150*
Analyzing for Chlorides	AASHTO T260	*148*
	ASTM C114	*151*
	ASTM D1411	*152*
	FLDOT	*153*
	LADTD DOTD 502	*28*
	Ontario MT LS 411	*52*
	SHRP C-101	*150*
	VAT VT-AOT-MRD-20	*154,141*
Sealer Penetration	IDDOT	*58*
	NDDOT	*59*
	OKDOT OHD L-34	*60*
Freezing & Thawing Resistance	AASHTO T161	*155*
	ASTM C666 (Proc. A)	*156*
	RIDOT	*139*
	VADOT	*157*
	VAT	*22*
Deicer Scaling Resistance	ASTM C672	*158*
Gas & Vapor Transmittance		
Water Vapor	ASTM E96	*159*
	ASTM D1653	*160*
	Alberta T & U B390	*120*
	and BT001	*136*
	IDDOT	*161*
	NCHRP 244; Ser. I, II, III	*9*
	NDDOT	*162*
	NYDOT 717-1E	*137*
	OKDOT OHD L-35	*163*
	RIDOT	*139*
	US Army COE	*71*
Carbon Dioxide	Nordtest NT Build 300	*164*
Alkali Resistance	Alberta T & U B390	*120*
	and BT002	*165*

*See Glossary of Terms and Acronyms.

TABLE 15
TESTING PROCEDURES THAT HAVE BEEN USED IN CONJUNCTION WITH SEALERS
(Continued)

Description	Test Method*	References
Abrasion Resistance	AASHTO T135	*69*
	AASHTO T136	*69*
	Alberta T & U B390	*120*
	and BT001	*136*
Accelerated Weathering (UV Exposure)	ASTM G53	*166*
	NCHRP 244; Ser. IV N & S	*9*
Carbonation Resistance	ETI (Spain)	*167*
Skid Resistance	ASTM E303	*168*
	ASTM E501	*169*
	ASTM E524	*169*
	AASHTO T278	*170*
Corrosion Resistance (Embedded Rebars)		
Impressed Current	FLDOT FM5-522	*171*
Impressed Voltage	WIDOT	*172*
Corrosion Potential	ASTM C876	*173*
Corr. Potential, Current, & Instant Off Potent.	FHWA	*174*
Electrical Resistance	ASTM D3633	*176*
Water Repellency	Danish Tech. Inst. 291-M-0070	*164*
D. Tests for the Condition of Existing Sealed Surfaces		
Chloride Penetration Resistance	--	*177*
	OKDOT OHD L-40	*61*
Rapid Chloride Permeability	AASHTO T277	*178*
	ASTM C1202	*175*
	VADOT	*157*
Surface Electrical Resistance	SHRP C-101	*150*
		179
Surface Absorption	British Stds. BS1881	*180*
	RILEM II.4	*181*
	SHRP C-101	*150,179*
Water Permeability	CLAM	*4*
Air Permeability	Figg	*4*
Skid Resistance	ASTM E303	*168*
	ASTM E501	*169*
	ASTM E524	*169*
	AASHTO T278	*170*

*See Glossary of Terms and Acronyms.

TABLE 16
SEALER QUALIFICATION PROCEDURES USED BY HIGHWAY AGENCIES

Qualification Procedure	Number of Highway Agencies Using	% of Highway Agencies Using*
Prescription	11	20
Internal Testing	30	57
External Testing	10	19
Vendor Data	21	39
Other Data	4	7

*Of the 53 highway agencies reporting sealer use to some degree.

TABLE 17
TESTING PROCEDURES USED FOR SEALER EVALUATION AND ACCEPTANCE BY HIGHWAY AGENCIES

Testing Procedure	Number of Highway Agencies Using	% of Highway Agencies Using*
None	15	28
Absorption	23	43
Chloride Ion Penetration	26	49
Water Vapor Permeability	17	32
Sealer Penetration Depth	8	15
Rapid Chloride Permeability Test	3	6
Impressed Current	2	4
Corrosion Potential of Rebar	1	2
Concrete Scaling Resistance	4	8
Freeze-Thaw Durability	4	8
Skid Resistance	2	4
Long-Term Field Performance	2	4
Specification for Linseed Oil	3	6

*Of the 53 highway agencies reporting sealer use to some degree.

product need to be included in a rational approach to the overall question of concrete protection on a case-by-case basis.

Regarding product qualification testing, rational test methods need to be developed to specifically address concrete sealers and encompass the physio-chemical properties by which they perform and the use/environment factors to which they are subjected. Ideally, only two tests are needed—chloride screening (initial and as a function of exposure conditions and time) and skid resistance (for barrier coating types of sealers on traffic surfaces, except for cases where tined or grooved surfaces are involved). Chloride screening is really the crux of the matter, and the performance of sealers measured by that parameter over time under expected field conditions can be made to include the effects of weathering, abrasion, alkalinity, and freeze-thaw. It is simpler to evaluate the effects of these variables individually, but then difficult to assess combined effects.

Product quality assurance testing needs only to concentrate on specific key properties or characteristics of the sealer that can be monitored to reveal changes in manufacture or from storage. Fingerprinting by use of infrared spectrographic analysis or other means and determination of solids content (for sealers in solution with carriers) should provide effective means of accomplishing this goal.

Field application quality assurance testing includes two areas. First, the concrete substrate to which a sealer is to be applied should receive characterization testing to assure compatibility. The most important factors that need to be evaluated in this regard are moisture content and cleanliness of the surface. The relatively simple test procedures shown under item B of Table 15 should do in this regard. Second, field application quality assurance testing needs to confirm that proper sealer application rates and procedures have been used. Any of the methods that express variations in surface properties, calibrated for the particular surface/sealer combination, might be used. These methods include surface electrical resistance, surface absorption, and air, or water, permeability devices listed under group D of Table 15.

Field testing for assessment of sealer reapplication needs and product performance should be carried out on a regular basis. The primary concern here is the effectiveness of the sealer, which can be determined only by measurement of chloride penetration. The sealed surface also needs to be assessed as to its effectiveness in continuing to screen chlorides. Both of these conditions can be evaluated using the testing procedure "Chloride Penetration Resistance" under group D of Table 15. Because coring or drill sampling is involved to accomplish this, it is suggested that a well-conceived sampling plan of limited chloride penetration resistance testing be used in conjunction with one of the simple surface condition tests

TABLE 18
FIELD PERFORMANCE TESTING OF SEALERS BY HIGHWAY AGENCIES

Testing Procedure	Number of Highway Agencies Using	% of Highway Agencies Using*
None	36	68
Yes, but not specified	2	4
Cores	1	2
Chloride Sampling	10	19
Sealer Penetration Depth	2	4
Electrical Resistance	1	2
Water Flood (Decks)	2	4
Visual Observation; Scaling Rating	2	4

*Of the 53 highway agencies reporting sealer use to some degree.

under group D of Table 15 to provide detailed coverage with minimal coring/drilling and laboratory testing.

A MODEL TESTING SPECIFICATION: ALBERTA TRANSPORTATION AND UTILITIES

Currently, no highway agencies have concrete sealer programs that meet the goals recommended in the preceding section. However, the one currently used by Alberta Transportation and Utilities (AT&U) comes the closest. In 1983, the Bridge Engineering Branch of AT&U began to develop a performance based specification for sealers where (*184*):

- Most testing costs are paid by industry rather than the tax payers;
- Testing for approval is done by approved private laboratories;
- Both coatings and penetrants are acceptable in different applications;
- Performance requirements are identified to industry so as to stimulate innovation and improved products;
- Data, submitted by manufacturers for approval, becomes the property of AT&U and is disseminated in approved lists when requested by consultants and government agencies, which serves as a free advertising incentive to the product manufacturers; and
- Test methods are designed to be realistic and economical with the result that AT&U's data base has grown.

Alberta identifies several types of sealers on which the testing program is based (*123*):

- Type 1 (General): Penetrating sealers for use on traffic surfaces.
  - Type 1a: For use under relatively dry conditions (sheltered areas).
  - Type 1b: For use on typical outdoor locations (e.g., bridge decks).
- Type 2 (General): Clear, film-forming sealers for use on non-traffic bearing surfaces.
  - Type 2a: One-component product for use by less experienced personnel.
  - Type 2b: Two or more component coatings for use by experienced contractors in areas requiring higher degree of waterproofing.
- Type 3: Pigmented film-forming sealers for use on elements that are highly exposed to public view involving aesthetic considerations.

The kinds of tests covered by the AT&U specification are (*120,121,136,165*):

- Solids content of Type 1 sealers,
- Spectrographic analysis of the sealer,
- Water vapor transmission,
- Waterproofing,
- Waterproofing after abrasion (for Type 1 sealers),
- Resistance to alkalinity (for Type 1 sealers),
- Hiding power (for Type 3 sealers), and
- Application rate.

The AT&U Specification B88—December 92, "Specification for the Supply of Concrete Sealers" (*123*) is provided in Appendix D.

CHAPTER FIVE

APPLICATION METHODS, RATES, AND COSTS

SURFACE PREPARATION

Before applying sealers, it is necessary to carry out appropriate surface preparation on the concrete, which was discussed briefly in Chapters 2 and 4. This is especially important on bridge decks and other trafficked surfaces where oil, grease, rubber, asphalt, and other organic contaminants are present. These areas need to be shot- or sand-blasted prior to the application of sealers to facilitate bonding or curing of the sealer and to open pores in the concrete so that the sealer can penetrate (*39*). Also, when applying a silane or siloxane for the first time to a concrete surface that is more than 1 year old, the carbonated layer at the surface of the concrete must be removed (as was discussed previously in Chapter 3).

It is important that manufacturer's recommendations regarding surface preparation for the specific product used be meticulously followed.

APPLICATION METHODS

In the questionnaire survey, sealer manufacturers were solicited for their views on the types of application methods recommended for their products (Table B-1, Appendix B). A summary of the results appears in Table 19. Air-less spraying appears to be the most favored technique and squeegee the least, although results vary for the individual generic types of sealers. Air-less spray or roller appears to be the favored method with acrylics and siloxanes. For silanes, the choice appears to be roller or air-less spray, and for epoxies, roller is preferred. The data are not sufficient, however, for linseed oil to indicate the choice.

APPLICATION RATES

Recommended application rates for sealers are highly variable within generic sealer type groups, as indicated from the sealer manufacturers questionnaire survey (see Table 20). Mostly, this has to do with the amount of carrier (if any) used and the number of coats applied. Because the available information is inconsistent, it was not practical to separate the effects of those factors in this discussion. However, the mean application rates are identical for all of the generic sealer type groups listed except linseed oil and the data available for the linseed oil are too few to permit its consideration in this comparison anyway.

A compilation of data on sealer application rates from the technical literature (Table 21) also shows considerable variability within the generic sealer types. However, it does not reveal the consistency of mean values between generic types that the manufacturers data does.

COSTS

Sealer cost data were derived from three sources—the sealer manufacturer and the highway agency questionnaire surveys conducted for this synthesis (see Appendices A and B) and the technical literature. The sealer manufacturers' cost data, which are material costs only, are presented in Table 22. As was the case with recommended application rates, costs vary widely within generic sealer type groups. However, the mean values among generic types appear to be relatively constant, except for linseed oil. As expected, linseed oil is considerably lower in material cost. The wide range in individual prices is largely due to the amount of carrier or diluent used, as in the case of application rates.

The cost data from the highway agency questionnaire survey are installed costs of concrete sealers and are presented in Table 23. In this case, outlier data were eliminated using a standard

TABLE 19
RECOMMENDED APPLICATION METHODS FROM MANUFACTURERS' QUESTIONNAIRE SURVEY

Sealer Generic Type	Number of Products	Method Recommended, % of Products					
		Squeegee	Roller	Broom	Spray: Air	Spray: Air-less	Other*
Acrylics	9	33	78	44	33	89	11
Epoxies	12	33	100	67	75	58	8
Linseed Oil	1	0	0	0	100	100	0
Silanes	22	36	91	77	45	86	0
Siloxanes	13	38	69	46	46	77	8

*Low pressure pump; flooding

TABLE 20
MANUFACTURER'S RECOMMENDED APPLICATION RATES FROM QUESTIONNAIRE SURVEY

Sealer Generic Type	Number of Products	Recommended Application Rates (ft²/gal)*	
		Mean	Range
Acrylics	9	155	50-300
Epoxies	12	155	110-250
Linseed Oil	1	450	--
Silanes	22	155	110-400
Siloxanes	13	155	125-400

*Ft²/gal = 40.74 x m²/l.

TABLE 21
SEALER APPLICATION RATES FROM THE TECHNICAL LITERATURE *(33,85,185)*

Sealer Generic Type	Number of Products	Application Rates (ft²/gal)*	
		Mean	Range
Acrylics	18	210	105-325
Epoxies	19	225	100-400
Linseed Oil	1	400	--
Silanes	11	120	75-200
Siloxanes	4	175	100-350
Chlor. Rubbers	4	215	100-400
Stearates	2	175	150-300
Silicates	2	135	120-150
Silicones	3	180	110-245
Mineral Gums	1	100	--

*Ft²/gal = 40.74 x m²/l.

TABLE 22
SEALER MATERIAL COST FROM MANUFACTURER'S QUESTIONNAIRE SURVEY

Sealer Generic Type	Number of Products	Cost, F.O.B. Plant ($/gal)*	
		Mean	Range
Acrylics	8	29.13	9.00-50.00
Epoxies	11	22.63	12.30-34.00
Linseed Oil	1	2.86	--
Silanes	12	21.05	13.95-38.00
Siloxanes	6	23.57	14.75-32.50

*In 1,000 gal lots. $/gal = 3.785 x $/l.

TABLE 23
SEALER INSTALLED COSTS FROM HIGHWAY AGENCY QUESTIONNAIRE SURVEY

Sealer Type	Number of Highway Agencies w/Data	Cost, $/yd²*	
		Mean	Range
Acrylics	3	2.26	1.28 - 3.00
Epoxies	5	5.04	2.20 - 7.20
Linseed Oil	6	0.67	0.50 - 0.90
Silanes	19	6.51	1.12 - 22.24
Siloxanes	6	2.98	1.70 - 4.00
Overall Average	6	4.90	1.19 - 10.98

*After elimination of outliers at the 90% confidence level using the Dixon Criterion *(187)* $/yd² = 0.836 x $/m².

TABLE 24
SEALER INSTALLED COST FROM THE TECHNICAL LITERATURE

Sealer Generic Type	Number of Products	Sealer Installed Cost $/yd²**	
		Mean	Range
Acrylics	19	3.96	1.71-7.38
Epoxies	18	5.58	3.15-8.82
Linseed Oil	8	1.44	0.54-2.70
Silanes	21	5.13	0.99-9.18
Siloxanes	4	4.59	2.07-8.28
Chlor. Rubber	3	2.97	2.61-3.42
Stearates	1	4.59	--
Silicates	2	4.59	3.42-5.67
Silicones	2	3.42	3.15-3.69
Mineral Gums	3	5.85	4.95-7.65

*Based on synthesis of information presented in the following references: *3,7-9,11,16,21,27,33,99,117, 174,188.*
**$/yd² = 0.836 x $/m².

statistical procedure. Nevertheless, the within-group ranges are still quite large. Also, the variability among the mean values for the generic sealer type groups is much greater than would be expected from the material price data presented previously in Table 22. However, installed cost data from the technical literature (Table 24) support the highway agency questionnaire survey data reasonably well. One study from the literature is not included in Table 24 because the cost data are presented in the form of regression equations as functions of job quantities. The data bases for the regressions were derived from 829 contract bid tabulations from 15 highway agencies across the United States. The equations are as follows (*186*):

for linseed oil: $C = 1.38 - 3 \times 10^{-5}\,Q + 10.9/Q^{1.01}$,
for silane/siloxane: $C = 8.65 + 7 \times 10^{-5}\,Q + 56.1/Q^{1.24}$, and
for acrylic: $C = 8.98 - 2.69 \times 10^{-6}\,Q$,

where C is the national average mid 1991 cost in $/yd^2 and Q is the job quantity in yd^2. Costs represented by these equations for various levels of job quantities are shown in Table 25. Linseed oil costs compare well with Tables 23 and 24, but the silane/siloxane and acrylic values are somewhat higher.

TABLE 25
MID 1991 NATIONAL AVERAGE SEALER INSTALLED COSTS FROM REGRESSION EQUATIONS FOR CONTRACT BID TAB DATA

Bid	Installed Cost, $/yd^2*		
Quantity (yd^2)	Linseed Oil	Silane/ Siloxane	Acrylic
10	2.44	11.88	8.98
100	1.48	8.84	8.98
1,000	1.36	8.73	8.98
10,000	1.08	9.35	8.95

*$/yd^2 = 0.836 x $/m^2.

CHAPTER SIX

SAFETY AND ENVIRONMENTAL ISSUES

GENERAL

The questionnaire survey of highway agencies revealed that only about half of the 45 agencies who use sealers and chose to report have no specific worker health and safety requirements relative to use of sealers. Nearly two-thirds have no specific environmental protection requirements (see Appendix A, Table A-6). However, in both respects, some states do require contractors to comply with the sealer manufacturer's recommendations and Material Safety Data Sheets (MSDS). The details are presented in Table 26.

Considering the obvious hazards to both personnel and the environment from many of the products used as concrete sealers, the cited figures would seem to be low. The only explanation that can be offered is that the question was poorly presented in the survey form and the response received reflects a misunderstanding of the nature of the information sought. Fortunately, sealer manufacturers are, in general, required by federal regulations to compile MSDS for their products. The MSDS contain detailed information on the following four areas: (1) worker safety, (2) fire safety, (3) environmental considerations, and (4) precautions for handling and storing. Because MSDS were requested from sealer manufacturers responding to the manufacturer's questionnaire survey, they will provide the data bases for the four topical areas.

Obviously, the manufacturer's recommendations and the MSDS should be read, understood, and fully complied with in the application, storage, handling, and disposal of concrete sealer products. Individual sealers have specific characteristics that cannot be discussed in sufficient detail in this Synthesis. The following sections provide a general overview of worker safety and environmental issue areas.

WORKER SAFETY

Virtually all concrete sealers are potential skin, eye, and respiratory irritants. They are also gastrointestinal irritants, but this is not a common entry mode. None of the types of concrete sealer materials considered in this Synthesis are currently believed to be carcinogens (cancer producing). In general, the Hazardous Materials Information System (HMIS) health hazard ratings for sealer materials are slight (class 1) or moderate (class 2). However, when certain solvents or carriers are used (principally xylene and toluene), health hazard ratings rise to classes 2 to 3 (moderate to high). Solvents, diluents, or carriers in sealer mixtures are generally the primary source of potential worker health hazards. Methyl trialkoxysilane has been identified as a health hazard that attacks the retina of the eye and has been prohibited for use in sealer products (*123*). However, as observed under the discussion of silanes in Chapter 2, this silane is much too volatile for use in sealers and would not normally be used in sealer products. Table 27 presents a partial listing of potentially hazardous components of concrete sealer products and their exposure limits garnered from the available MSDS. More detailed information can be found in Table B-4 of Appendix B.

The most common symptoms of overexposure to sealers include skin burns, itching, dermatitis, conjunctivitis, nausea, headache, and dizziness. The primary pre-existing medical conditions aggravated by exposure to sealers are skin and respiratory disorders.

Proper protection from sealers for personnel includes:

- Practice of good personal hygiene,
- Use of clean protective clothing,
- Wearing of proper eye protection,
- Use of impermeable boots and gloves,
- Provision of adequate ventilation, or respiratory protection,
- Location and proximity of eyewash stations and safety showers, and
- Use of barrier creme.

More detailed information summaries compiled from the MSDS are provided in Tables B-7 and B-8 of Appendix B.

FIRE SAFETY

In general, concrete sealers are flammable to varying degrees. Inorganic materials such as sodium or potassium silicate dissolved in water are, of course, totally nonflammable (HMIS fire hazard rating = 0). Some of the water-dispersed materials will also have very low fire hazard ratings. Conversely, those containing organic solvents may be quite flammable, with fire hazard ratings of 2 (moderate) or 3 (high). The volatile solvents also introduce explosion hazards, with the lower and upper explosive limit concentrations in the ranges of 1 to 2 percent and 7 to 12 percent, respectively (see Table B-4, Appendix B). Some of the active ingredients involved can also be quite volatile and flammable, such as methylmethacrylate monomer.

The extinguishing modes recommended for use for fires involving concrete sealer materials are those commonly used for organic chemicals — water fog, dry chemical, foam, alcohol foam, and carbon dioxide. Depending on the severity of the fire (amount and type of fuel involved), necessary protective equipment can range from a self-contained breathing apparatus to a full bunker gear with face-piece. In addition to extinguishing flames, the fire fighting strategy should include cooling sealer containers with water spray (see Tables B-4 and B-5, Appendix B).

Special fire and explosion hazards exist with some sealer materials. Acrylic monomers and the organic solvents used as diluents and carriers in many concrete sealers are volatile and their vapors are denser than air. This introduces the dangers of explosive vapors, in general, and "flashback" in particular. Also, some of the materials used in sealers can create toxic organic fumes when burned, as in the case of epoxies and urethanes (see Table B-6, Appendix B).

TABLE 26
WORKER SAFETY AND ENVIRONMENTAL PROTECTION IN SEALER USE FROM HIGHWAY AGENCY QUESTIONNAIRE SURVEY

	Number of Highway Agencies (% Reporting)*	
	Worker Health & Safety Requirements	Environmental Protection
Agencies Reporting	45	45
No Requirements	24 (53%)	28 (62%)
Specific Requirements:		
Comply with all Federal, State, and Local Regulations	6 (13%)	7 (16%)
Per Standard Specs. or Engineering Guidelines	3 (7%)	1 (2%)
Per Material Safety Data Sheets (MSDS)	5 (11%)	2 (4%)
Follow Manufacturers' Recommendations	9 (20%)	2 (4%)
Specify Protective Clothing/Equipment	4 (9%)	--
Manufacturer's Representative Responsible to Instruct Workers	2 (4%)	--
Contractor's Responsibility	4 (9%)	--
Pollution Protection Controls	--	6 (13%)
Use requires approval of State Environmental Protection Group	--	1 (2%)
Reporting Spills to State Environmental Agency Required	--	1 (2%)
Disposal only at Licensed Site	--	1 (2%)

*Note: Totals greater than 100% because some agencies that do not have specific requirements make these issues contractor's responsibilities, and other agencies have two or more requirements.

ENVIRONMENTAL CONSIDERATIONS

The general procedures followed in the event of an accidental spill of sealer product are to:

- Remove ignition sources;
- Ventilate the area, if necessary;
- Dike the spill area to prevent runoff to sewers and surface water courses;
- Pump or absorb the spill with filler materials and place in drums; and
- Flush the area with water to remove the last traces of material.

Waste sealer material should be disposed of in strict accordance with applicable local, state, and federal regulations. This may include interment in approved land fills, incineration, or polymerization (acrylics, epoxies, and urethanes) followed by normal disposal of bulk construction waste. Only inorganic silicate materials would likely be permitted to course directly into sanitary sewers. Evaporation of volatiles may be permitted, but this is becoming increasingly less likely. See Table B-8 in Appendix B for details on spill cleanup and waste disposal.

TABLE 27
EXPOSURE LIMITS FOR SOME SEALER INGREDIENTS FROM MSDS RECEIVED WITH MANUFACTURERS' QUESTIONNAIRE RESPONSES

	Exposure Limits (ppm—Unless otherwise noted)*			
	OSHA	ACGIH		
Material	PEL	TLV	STEL	Remarks
Xylene	100	100	150	Solvents for acrylics, epoxies, and urethanes
Toluene				
Mineral Spirits	100	100		Solvent for linseed oil, silane, and siloxane
Aromatic Petroleum Solvent	100	100		Solvents for urethane
Methyl Isobutyl Keytone	100	50		
Methanol	200	200	250	Carriers for silane and siloxane.
Ethanol	1,000	1,000	None	Methanol or ethanol also released upon
Isopropanol	400	400	500	hydrolysis of silanes and siloxanes.
Linseed Oil	500	100		Primary sealer ingredient
Methylmethacrylate Monomer	100	100		Acrylic resin
Benzoyl Peroxide		5 mg/m^3		Initiator for acrylics
Cumeme		50		Promoters for acrylics
Cobalt Octolate		0.1 mg/m^3		
Manganese Carboxylate		5 mg/m^3		
Bisphenol A Diglycidyl Ether	None	None	None	Epoxy resin components
Polyamide Resin				
Isooctyltrimethoxysilane	200	200		Primary sealer ingredient
Ethyl Silicate	100	10	None	Siloxane reaction products
Acetic Acid	10	10	15	
Free Aromatic Diisocyanate	0.02	0.02		Urethane reaction product

*PEL = permissible exposure level; TLV = threshold limit value; STEL = short-term exposure limit.

It is predicted that the amendments to the Clean Air Act passed by the U.S. Congress in 1990 are likely to lower the concentration limits of volatile organic compounds (VOC) in concrete sealers (*189*). VOC's react with oxides of nitrogen in the presence of sunlight to form components of smog. The Environmental Protection Agency sets the VOC limits. Highway agencies that have established values for "waterproofing sealers" include Phoenix, Los Angeles, San Diego, and San Francisco at 400 grams per liter (3.33 lb/gal), and New Jersey and New York City at 600 grams per liter (5.00 lb/gal). The kinds of chemicals involved are methane-type (aliphatic) materials such as the mineral spirits and alcohols used as solvents and carriers in sealers. Therefore, it is nearly certain in the future that there will be a shift toward water-based sealers. It is questionable that much use can be made of exempt solvents because they are generally chlorinated hydrocarbons and also possess environmental liabilities. However, both water and exempt solvent carriers are believed to compromise the penetration effectiveness of the sealers (*31*).

PRECAUTIONS FOR HANDLING AND STORING

Concrete sealers are invariably designated on the MSDS to be chemically stable products. However, because they frequently contain highly volatile and flammable components, precautions have to be observed in handling and storing them. Conditions to avoid include high temperatures, moisture, high humidity, proximity to ignition sources or contamination, and static charge buildup. Also, some materials become unstable with aging, and therefore should be subject to limited storage time. Others are subject to photochemical reactions and should not be exposed to sunlight for extended periods.

Because of potential reactivity in the event of container leakage or rupture, sealers should not, in general, be stored together with strong acids, oxidizing agents, amines, amides, or peroxides. Storage should be in a cool, dry location with good ventilation and no ignition sources. Containers should be grounded. Sealers should not be allowed to freeze. Cutting, grinding, or welding operations should not be permitted on containers which contain, or previously contained, sealer products. Additional information on precautions for handling and storing sealers can be found in Table B-8 of Appendix B.

CHAPTER SEVEN

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

General

Sealing of concrete surfaces can be used to delay the effects of deterioration such as deicer scaling of inferior concrete or chloride-induced reinforcing bar corrosion if deterioration is not already underway. Sealing is the lowest first cost method and potentially the lowest life-cycle cost procedure, especially when service life extension expectations are under 50 percent. Over 80 percent of the highway agencies in North America report using concrete sealers to at least a limited extent. Currently, hundreds of sealer products comprising two dozen or more generic types (depending on how one categorizes them) are available on the market, and no consensus exists on standardized programs of tests for evaluating them.

In general, no sealer can fully prevent any of the various potential forms of concrete deterioration. However, good quality products from all three classes of sealers (water repelling, pore blocking, and barrier coating) can retard the attack of all types of concrete deterioration (except, possibly, alkali-aggregate reaction) and can mitigate the effects of attack in progress by some of the deteriorative mechanisms.

Regarding the frequent accusations directed at sealer manufacturers for purported overstatement of penetration depths, the data do not reveal that this is a general practice. Ranges of advertised penetration depths are not significantly different from users test results reported in the technical literature for the major types of sealers.

Sealer Performance

Sealer performance is difficult to assess. Generalized, relative ratings synthesized from laboratory testing ranked dual systems as the top performing type from among 12 generic classifications of sealers. Dual systems usually consist of a water-repellent primer and a pore-blocking top coat, typically alkylalkoxysilane and polymethylmethacrylate, respectively. Gum resins, urethanes, silanes, chlorinated rubbers, epoxies, siloxanes, silicones, and stearates displayed average performances. Acrylics, linseed oil, and silicates performed poorly in laboratory testing. Limited field test results support most of these rankings with the most notable exception being acrylics, which perform considerably better in the field than in lab tests. These rankings can still be misleading, however. Silanes and siloxanes, for example, display ranges of performance from best to worst, particularly in the field. Therefore, their rankings, which represent the averages of performance test results, are mediocre. The primary reason for the varied performances reported for silanes and siloxanes likely is the result of misapplication of these materials to concretes that are too wet, too old (carbonated), or too low in quality (porous, high water/cement ratio). The field performance of boiled linseed oil is generally good, but service life (reapplication time) is short—typically 2 to 3 years. The reason for poor results in laboratory testing of linseed oil seems to stem from testing before polymerization of the linseed oil has occurred.

Sealer Testing

Sealer testing needs encompass the following areas: product qualification, product quality assurance, field application quality assurance, and field testing for assessment of sealer reapplication needs and product performance. Generally, only the first of these is currently being addressed by highway agencies. A wide range of test procedures are used for product qualification testing. Most of these procedures (about 80 percent) are borrowed from other disciplines and areas, and their applicability to concrete sealers is questionable. This is probably the factor largely responsible for the diverse performance of given products among highway agencies. Product qualification tests need to be rational, related to the variables that actually affect field performance (to the extent possible). Testing procedures developed by Alberta Transportation and Utilities are a good start toward rational product qualification and quality assurance testing. Testing needs for application quality assurance, reapplication requirements, and product performance in the field may be satisfied with currently existing tests, but additional field studies are needed in this regard. Testing for proper sealer application rates should be included in product qualification and field quality assurance testing.

Sealer Selection

The selection of applicable sealers by generic type should be based on the following: concrete substrate conditions (age, water/cement ratio, chloride content, and reinforcement corrosion potential); service (exposure to abrasion, chlorides, UV); moisture environment; and recoating properties. Inputting appropriate values for the above variables into the selection matrix presented in Table 11 will assist in identifying suitable sealers by generic type(s).

The selection of a specific sealer product, once the suitable generic type(s) are defined, should be based on life-cycle cost analyses of candidate products. Candidate sealer products are those materials identified as acceptable in a rational laboratory program for product qualification. The life-cycle cost analyses depend on reasonable definition of sealer service life (reapplication time) that can be estimated from chloride penetration testing (see Appendix C).

In general, for the use of sealers to be economical, the chloride ion content at the depth of the shallowest 1 percent of the reinforcing steel will be less than 0.6 kg/m^3 (1.0 lb/yd^3), and corrosion potential (half-cell) readings will be more positive than −250 mV CSE (*17*).

The types of sealers that appear to be most suitable for use in highway applications are:

- Water repellents:
  - Alkylalkoxysilane
  - Oligomeric alkylalkoxysiloxane
- Pore blockers:
  - Gum resin in solvent
  - Boiled linseed oil in solvent
- Pore blockers or barrier coatings (depending on the amount of dispersant used):
  - Epoxy resin
  - Urethane
  - Acrylic
  - Chlorinated rubber
- Dual systems:
  - Alkylalkoxysilane primer and acrylic top coat.

Environmental and Safety Considerations

Potentially stricter federal environmental protection air quality standards may limit future use of photosensitive VOCs that are commonly employed as diluents or carriers for sealers. The necessary change to exempt solvents or water dispersions (emulsions or latices) may result in decrement of sealer properties, especially penetration. Research, therefore, is needed in this area.

Manufacturers' recommendations must be closely followed regarding sealer application methods; the use, handling, and storage of sealer materials; and protection of personnel and the environment.

RECOMMENDATIONS

Based on the aforementioned conclusions and findings of this synthesis, the following specific recommendations are tendered:

- Develop a national standard testing specification for concrete sealers consisting of testing protocols that address the following: product qualification, product quality assurance, field application quality assurance, and field assessment of reapplication needs and product performance. The variables involved in testing for product qualification should, to the extent feasible, imitate expected field conditions covering the various levels of service and concrete substrate conditions that may be encountered.

  Testing for required and actual sealer application rates should be included in the product qualification and field application quality assurance testing phases, respectively.

In order to promote rational sealer use based on life-cycle costs:

- Develop national data bases of acceptable sealer products for various levels of service in highway applications based on a national standard testing specification for sealers.
- Develop geographically subdivided national data bases on in-place sealer costs and service lives for various levels of service in highway applications. Data bases for cost and service life are needed anyway for bridge and pavement management systems.
- Develop data bases that reflect the relationships between concrete substrate conditions and the benefits that can be obtained from the application of sealers.

GLOSSARY OF TERMS AND ACRONYMS

AASHTO—American Association of State Highway and Transportation Officials.

ACI—American Concrete Institute.

acrylics—thermoplastic polymers based on acrylic acid esters.

Alberta T&U—Alberta Transportation and Utilities.

aliphatic—chain-type organic (hydrocarbon) molecules.

ASTM—American Society for Testing and Materials.

barrier coat sealers—concrete sealers that do not penetrate pores, but form measurable surface coatings.

boiled linseed oil—a drying oil made from flax seed; the major component of oil-based paints.

carbonation—chemical reaction between free lime in concrete and carbon dioxide in the atmosphere forming calcium carbonate.

chlorinated rubber—synthetic rubber hardened by reaction with chlorine and dispersed in solvent.

contact angle—the angle formed between a solid surface and a drop of water on the surface— a measure of water repellency.

cps—centipoise, unit of dynamic viscosity in the c.g.s. system.

CSE—Copper sulfate electrode in the cooper-copper sulfate half cell for measuring the corrosion potential of reinforcing steel in concrete.

CSH—Calcium silicate hydrate, basic structure of hardened cement paste.

depolarize—the action of oxygen at the cathode in an electrochemical corrosion cell that increases metal loss at the anode.

difunctional organic compounds—organic molecules containing two reactive sites.

dissolution—attack of concrete by very soft or pure water by solution of free lime.

emulsion—droplets of organic monomer stabilized by surfactants in water.

epoxies—a group of thermoset polymers based on (usually) the reaction product of bisphenol A and epichlorohydrin.

ester—product of the reaction between an organic acid and an alcohol.

FHWA—Federal Highway Administration.

gum resins—usually natural materials produced by plants and trees such as rosin, pine tar, and pitch.

HCP—hardened cement paste—the binder in concrete.

HMIS—Hazardous Materials Information System.

hydrolysis (hydrolyze)—reaction with water.

hydrophobic—water-repelling surfaces.

Kelvin (equation)—Lord Kelvin's equation relating meniscus curvature radius (minimum pore radius) to relative vapor pressure in capillary condensation.

latex (latices)—the products of emulsion polymerization consisting of droplets of polymer stabilized by surfactants in water.

mer—the basic repeating unit in an organic polymer.

MSDS—Material Safety Data Sheets.

oligomerous (oligomeric)—short chain organic polymers composed of few (up to ten) repeating units.

organofunctional—portions of organosilicon molecules that react with organic molecules.

organosilicon—molecules based on inorganic silicon but containing organic (hydrocarbon) groups.

polycondensation—polymerization with the evolution of water.

polyesters—polymers resulting from the reaction between difunctional alcohols and anhydrides of dibasic organic acids.

polyfunctional organic compounds—organic molecules containing more than one reactive site.

pore-blocking sealers—concrete sealers that enter and block the pores leaving no measurable surface coating.

REMR—Repair-Evaluation-Maintenance-Rehabilitation program of the U.S. Army Corps of Engineers Waterways Experiment Station. Dial (601) 634-4223 to connect. The pertinent telecommunications parameters are as follows: Baud Rate: 1200 or 1400; Emulation: VT-100; Data Bits: 8; Stop Bits: 1; Parity: None.

For additional information, contact CEWES-SC-CA/Roy L. Campbell, Sr., 3909 Halls Ferry Road, Vicksburg, Mississippi, 39180-6199, Phone (601) 634-2814.

saponification—reaction between a fatty acid and an inorganic base producing a soap (e.g., linseed oil and free lime in concrete).

SHRP—Strategic Highway Research Program.

silane—monomeric organosilicon molecule.

silicates—silicon-based sealers that contain no organofunctional groups.

silicon functional—portions of organosilicon molecules that react with inorganic molecules.

siliconate—organosilicon molecule in which hydroxyls and an alkali metal oxide occupy the silicon functional positions.

silicone—organosilicon molecules that contain two silicon functional and two organofunctional groups.

siloxane—organosilicon molecule consisting of 2 to 5 repeating units.

stearates—soaps or metallic salts derived from fatty acids.

Stoddard solvent—a petroleum distillate primarily used for dry cleaning.

thermoplastic polymers—polymers that can be softened and remolded by applying heat.

thermoset polymers—polymers that cannot be softened and remolded by applying heat.

triglycerides—esters from reactions between fatty acids and glycerol.

unsaturated organic compounds—hydrocarbon molecules containing reactive double or triple chemical bonds.

urethanes (polyurethanes)—reactive resins resulting from reactions of isocyanates with polyols, polyesters, or polyethers.

vinyls—addition-type polymers.

VOC—Volatile Organic Compounds—photosensitive hydrocarbons that contribute to smog formation in the atmosphere.

water-repellent sealers—concrete sealers that penetrate pores and render pore surfaces water repellent.

wax beads—grain-size wax particles incorporated in concrete, which is subsequently heated, melting the wax, to produce internal sealing (process is no longer used).

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APPENDIX A

HIGHWAY AGENCY QUESTIONNAIRE AND REPLY SUMMARY TABULATIONS

This questionnaire was designed as a follow-up on the survey conducted by Whiting as part of a Strategic Highway Research Program (SHRP) project in 1989 (*2*). Responses were received from 55 of 63 agencies solicited. Combined with the Whiting survey, which had responses from 55 of 62 agencies polled (the District of Columbia was not polled), a total of 58 of the 63 agencies responded.

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM
NCHRP Project 20-5/Topic 24-12
"Sealers for Portland Cement Concrete Highway Facilities"

QUESTIONNAIRE FOR STATE & PROVINCIAL HIGHWAY AGENCIES

NOTE: The purpose of this questionnaire is to update and expand upon data that your agency provided to Dr. David Whiting of Construction Technology Laboratories about 4 years ago on the use of concrete sealers. That study was carried out under SHRP Contract C-101. The results of that questionnaire were published by Dr. Whiting in Transportation Research Record No. 1284 in 1990. Tables 1 and 2 from Dr. Whiting's paper, summarizing the questionnaire responses, are reproduced and appended to this form.

1. Are there any changes in the data in the attached Tables 1 and 2 from Dr. Whiting's paper for your state (province)? ______. If so, please provide details.______________________________
____
____
____

2. If your state (province) maintains an approved product list for concrete sealers, please provide a copy of the current list.

3. If your state (province) has instituted new testing procedures (or revised existing ones) for concrete sealers since October 1988, please supply copies. Notice that this applies to the following:
   (a) Product approval rating tests
   (b) Routine product quality assurance tests
   (c) Field application quality assurance tests
   (d) Field tests for reapplication needs

4. Please describe your state's (province's) current experience with problems associated with:
   (a) Sealer application:______________________________
   ____
   ____
   (b) Sealer performance:______________________________
   ____
   ____

5. Please provide typical (average), current (1992) costs for applying each type of sealer material used by your state (province). Please include labor (plus burden), material, and overhead costs, if possible.

Material	Cost, $/sy	Includes

6. Does your state (province) impose requirements regarding worker health or safety relative to the use of any concrete sealer materials? ____. If so, please elaborate below:

7. Does your state (province) impose requirements regarding environmental impacts relative to the use of any concrete sealer materials? ____. If so, please elaborate below:

PLEASE RETURN THE COMPLETED QUESTIONNAIRE TO THE NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM'S CONSULTANT ON THIS PROJECT:

Dr. Philip D. Cady, P.E.
P.O. Box 158
Lemont, PA 16851-0158

ANY QUESTIONS REGARDING THE QUESTIONNAIRE SHOULD ALSO BE DIRECTED TO DR. CADY AT THE ABOVE ADDRESS OR BY PHONE (814)238-3215.

PLEASE RETURN COMPLETED QUESTIONNAIRE BY DECEMBER 31, 1992

TABLE A-1
SUMMARY OF RESPONSES—USE, APPLICATIONS, AND QUALIFICATIONS

STATE	EXTENT OF USE	APPLICATIONS	QUALIFICATION	PRODUCT LIST
AL	Lim.-L.O.	Decks	Prescription	NO
AR	Mod.-L.O./Exp.	Decks	Prescription	NO
CA	Ext.-L.O./Lim.	Decks,beams,piers,caps,appurtenances, barriers	Internal testing, vendor data	YES
CO	Lim.	Decks,sidewalks	Prescription	NO
CT	Mod.	Decks,appurtenances,barriers	Vendor data	YES
DE	Lim.	Decks,piers,caps,barriers,appurtenances	Vendor data	NO
FL	Lim.	Decks,beams,piers,caps,appurtenances	Internal testing ,vendor data	YES
GA	Ext.-L.O.	Decks	Prescription	YES
I D	Lim.-L.O.	Decks	Internal/external testing	NO
I L	Mod-L.O./Lim.	Decks,piers,caps,barriers appurtenances,pavements	Vendor data	YES
IN	Exp.	Decks	Internal testing	YES
I A	Mod.	Piers,caps,curbs,gutters	Internal testing	YES
KS	Ext.	Decks, appurtenances	Internal testing	YES
KY	Lim.	Decks	Vendor data	YES
LA	Exp.	Decks	Experimental only	NO
ME	Ext.-L.O./Lim.	Decks,piers,caps,barriers,appurtenances	Vendor and other data	NO
MD	Lim.-L.O.	Decks	Internal testing	NO
MA	Mod.	Appurtenances,barriers	Internal testing	YES
M I	Ext.-L.O./Lim.	Decks(L.O.),Piers	Internal/external testing	YES
MN	Exp.	Decks,barriers	Experimental only	YES
MO	Ext.-L.O.	Decks,barriers,appurtenances	Internal testing	NO
MT	Mod.-L.O.	Decks,beams,appurtenances	Internal/external testing	NO
NE	Mod.	Decks	Internal testing,prescription	YES
NV	Exp.	Decks	Experimental only	NO
NH	Ext.	Beams,piers,caps,walls,appurtenances, barriers	External testing, vendor data	YES
NJ	Exp.	Decks	Internal testing,prescription	YES
NM	Ext.	Decks,beams,caps,appurtenances	Internal testing,vendor data	YES
NY	Mod.	Decks,piers,caps,appurtenances,barriers	Internal testing	YES
NC	Ext.-L.O./Lim.	Decks,appurtenances	Certification	NO
ND	Ext.-L.O./Lim.	Decks	Internal testing	YES
OH	Mod.	Beams,appurtenances	Vendor data	YES
OK	Ext.	Decks,piers,appurtenances	Internal testing	YES
OR	Lim.	Beams,piers,caps,appurtenances	External testing,vendor data	YES
PA	Lim.	Decks,piers,caps,barriers	Internal testing	YES
R I	Lim.	Appurtenances	Internal testing	YES
SC	Mod.-L.O.	Decks	Prescription	NO
SD	Ext.-L.O.	Decks	Internal testing,prescription	YES
TN	Lim.	Decks	Internal testing	NO
TX	Ext.-L.O.	Decks	Prescription	NO
UT	Exp.	Decks,piers,barriers,appurtenances	Experimental only	YES
VT	Ext.-L.O./Exp.	Piers,caps,barriers,appurtenances	Internal testing	NO
VA	Lim.	Decks,appurtenances,pavement	Internal testing	YES
WA	Exp.	Decks,beams,piers,caps	External testing	NO
WV	Ext.	Decks,beams,appurtenances	Vendor data	YES
W I	Ext.	Decks	Internal testing	YES
WY	Mod./Lim.	Pavement/decks	Internal testing,vendor data prescription	YES

PROVINCE	EXTENT OF USE	APPLICATIONS	QUALIFICATION	PRODUCT LIST
AB	Ext.	Decks,beams,piers,appurtenances	External testing,vendor data	YES
BC	Ext.	Decks, appurtenances	Internal testing, vendor data	YES
MB	Lim.	Decks, curbs	Vendor data,prescriptipn	NO
NB	Lim.	Decks, appurtenances	Internal/external testing	NO
NS	Lim.	Decks,barriers	Internal testing	NO
ON	Lim.	Beams,barriers	Internal testing	YES
QE	Lim.	Piers,barriers,appurtenances	Internal testing	YES
SK	Lim.	Decks,barriers,appurtenances	AB DOT data	YES
YT	Lim.	Decks,appurtenances	By recommendation	NO

Note-Use categories abbreviated as follows:
Ext.-Extensive use.
Mod.-Moderate use.
Lim.-Limited use.
Exp.-Experimental use only.
L.O.-Use category refers to linseed oil only (i.e. Mod.-L.O.)

TABLE A-2
SUMMARY OF RESPONSES—TEST PROCEDURES AND PROBLEMS

STATE	TEST PROCEDURES	PROBLEMS		FIELD TESTS
	USED	APPLICATION	PERFORMANCE	
AL	not tested routinely	NO	NO	NO
AR	AASHTO M233-L.O.	NO	NO	NO
CA	NCHRP 244,absorption	YES	n/a	NO
CO	not tested routinely	YES	YES	NO
CT	rely on vendor test data	NO	NO	NO
DE	rely on vendor test data	NO	NO	NO
FL	Impressed current	YES	NO	YES-Chloride sampling
GA	ASTM D260-L.O.	n/a	Questionable	NO
I D	NCHRP 244,pen.depth,	n/a	n/a	NO
	vapor perm,skid no.			
I L	NCHRP 244, ASTM C 672	NO	NO	NO
I N	Field evaluation	NO	YES	YES-long term sampling
I A	AASHTO T259	NO	NO	NO
KS	ASTM C 642, AASHTO T259	YES	YES	YES-Chloride sampling
KY	rely on vendor test data	n/a	n/a	NO
LA	not tested routinely	NO	YES	YES-Chloride sampling
ME	rely on vendor and other DOT data	NO	NO	NO
MD	only use L.O.	YES	n/a	NO
MA	similar to NCHRP 244	NO	NO	YES-visual inspection
M I	AASHTO T 259	NO	NO	NO
MN	Field evaluations	YES	YES	YES-Chloride sampling
MO	ASTM C 672,C 642,AASHTO T 259	NO	NO	NO
MT	L.O. recently eliminated from specs.	n/a	n/a	NO
NE	AASHTO T 259	YES	NO	YES-Chloride sampling
NV	not tested routinely	NO	Unknown	YES-Chloride sampling
NH	NCHRP 244	NO	NO	NO
NJ	Saline absorption	NO	NO	YES-visual scale ratings
NM	ASTM C642, AASHTO T 259	NO	NO	NO
	OK DOTpen. depth,vapor perm			
NY	similar to NCHRP 244	NO	NO	NO
NC	not tested routinely	YES	YES	NO
ND	ASTM C642, AASHTO T 259	NO	NO	NO
	OK DOT pen. depth,vapor perm			
OH	rely on vendor test data	NO	NO	NO
OK	ASTM C642, AASHTO T 259	NO	NO	YES-water flood and
	pen. depth,vapor perm			observe
OR	NCHRP 244,ALB&FL tests	NO	NO	NO
PA	AASHTO T 259	n/a	n/a	NO
R I	Chloride intrusion	NO	Unknown	NO
SC	not tested routinely	n/a	Questionable	NO
SD	used as curing compounds only	YES	n/a	NO
TN	AASHTO T 259	n/a	n/a	NO
TX	not tested routinely	NO	NO	NO
UT	Freeze-thaw test	Unknown	Unknown	NO
VT	AASHTO T259(modified),absorption	NO	YES	YES-Chloride sampling
VA	ASTM C 666, AASHTO T 277	YES	YES	YES-field cores
WA	NCHRP 244	NO	YES	NO
WV	rely on vendor test data	NO	NO	NO
W I	AASHTO T 32, T 259, FL test	NO	n/a	YES-field cores
WY	ASTM C 642, OK DOT vapor prem,	NO	YES	YES
	pen. depth			

Note: L.O.- Linseed oil.

PROV.	TEST PROCEDURES	PROBLEMS		FIELD TESTS
	USED	APPLICATION	PERFORMANCE	
AB	Water absorption	NO	NO	NO
BC	AB and OK DOT test procedures	YES	n/a	NO
MB	rely on vendor test data	NO	NO	NO
NB	n/a	NO	YES	YES-water flood
NS	n/a	NO	YES	NO
ON	Water/saline absorption,ASTM C672	NO	YES	NO
	AASHTO T277			
QE	similar to NCHRP 244	YES	n/a	NO
SK	rely on AB DOT test data	NO	NO	NO
YT	not tested routinely	unknown	unknown	NO

TABLE A-3
DOT QUESTIONNAIRE—SUMMARY OF RESPONSES: SEALER TYPES AND EXTENT OF USE

		Types of Sealer Recently Used or Approved for Use													
				Epoxy			Silane		Siloxane		Silane/		Synthetic		
Highway Agency	Extent of Use	Acrylics	Linseed Oil	Solvent Dispersed	Water Dispersed	Polyester	Solvent Dispersed	Water Dispersed	Solvent Dispersed	Water Dispersed	Siloxane Mix	Silicates	Gum Resins	Stearates	Urethanes
Alabama	None														
Arkansas	Extensive		X												
California	Limited							X							
Colorado	Limited						X	X							
Connecticut	Moderate				X		X	X	X				X	X	
Delaware	Limited						X								
Dist. of Co.	Moderate		X												
Florida	Limited						X		X						
Georgia	Experimental														
Idaho	Limited		X				X		X						
Illinois	Moderate	X	X	X	X		X	X	X				X		
Indiana	Extensive			X			X		X				X		
Iowa	Moderate			X									X		
Kansas	None														
Kentucky	Limited				X		X		X			X	X		
Louisiana	Experimental						X								
Maine	Extensive		X				X								
Maryland	Limited		X												
Mass.	Moderate				X		X	X	X				X	X	
Michigan	Extensive		X				X		X					X	
Minnesota	Limited	X		X	X		X	X	X			X	X		
Mississippi	None														
Missouri	Extensive		X												
Montana	Moderate						X								
Nebraska	Moderate						X								
Nevada	Experimental								X						
New Hamp.	Extensive	X	X				X		X						
New Jers.	Experimental						X						X	X	
New Mexico	Extensive						X								
New York	Moderate			X			X	X	X					X	
North Car.	None														

TABLE A-3 Continued

Highway Agency	Extent of Use	Acrylics	Linseed Oil	Epoxy: Solvent Dispersed	Epoxy: Water Dispersed	Polyester	Silane: Solvent Dispersed	Silane: Water Dispersed	Siloxane: Solvent Dispersed	Siloxane: Water Dispersed	Silane/ Siloxane Mix	Silicates	Synthetic Gum Resins	Stearates	Urethanes
		Types of Sealer Recently Used or Approved for Use													
North Dak.	Extensive		X				X								
Ohio	Extensive			X	X		X	X	X				X	X	
Oklahoma	Extensive						X						X	X	
Oregon	Limited	X		X			X								
Penn.	Limited			X	X		X	X	X		X	X	X		
Rhode Isl.	Limited				X										
South Car.	Moderate						X								
South Dak.	Extensive		X												
Tennessee	Limited		X				X								
Texas	Extensive		X												
Utah	Limited	X		X			X	X	X				X	X	
Vermont	Extensive		X												
Virginia	Limited	X	X	X	X	X	X	X	X			X	X	X	X
Washington	Limited		X	X			X								
W. Virginia	Extensive						X	X					X		
Wisconsin	Extensive			X			X		X						
Wyoming	Limited						X	X	X				X		
Alberta	Extensive	X		X			X	X	X		X				X
Brit. Col.	Extensive						X								
Manitoba	Limited						X								
New Bruns.	Limited			X			X					X	X		
Newfound.	Experimental						X			X					
Nova Scotia	None														
Ontario	Limited	X		X			X		X		X		X	X	
Quebec	Limited						X		X						
Saskatch.	Limited	X		X			X	X	X		X				X
Yukon Ter.	Limited			X											

TABLE A-4
DOT QUESTIONNAIRE—SUMMARY OF RESPONSES: APPLICATIONS AND REMARKS

Highway Agency	Applications: Decks	Beams	Piers; Caps	Parapets	Median Barriers	Abutments	Sidewalks	Curb & Gutter	Approved Product List	Remarks
Alabama									--	No longer use any concrete sealers. Use L.O., silicate, & silane in past.
Arkansas	X								No	
California	X	X	X	X	X	X			Yes	Linseed oil no longer used.
Colorado	X						X		Yes	
Connecticut	X			X	X	X			Yes	
Delaware	X		X	X	X	X			No	Have not used L.O. in 20 yr.--consider ineffective.
Dist. of Co.							X	X	No	
Florida	X	X	X	X		X			Yes	
Georgia	X								No	Recently discontinued L.O. use. Currently testing silanes & siloxanes.
Idaho	X								No	
Illinois	X		X	X	X	X			Yes	Moderate use of L.O.; use of others limited.
Indiana	X								Yes	
Iowa			X					X	Yes	
Kansas									--	Current moratorium on sealer use. Tests found sealers ineffective.
Kentucky	X								Yes	
Louisiana	X								No	
Maine	X		X	X	X	X			No	Use linseed oil 98% of time.
Maryland	X								No	
Massachusetts				X	X	X				Yes
Michigan	X		X						Yes	Extensive use of linseed oil; others limited.
Minnesota	X				X				Yes	All except solvent-dispersed silane experimental only.
Mississippi									--	Do not use sealers.
Missouri	X			X	X	X			No	Use linseed oil only (by specification).
Montana	X	X	X	X		X			No	Primarily silane treatments on bridge decks. Stopped using L.O. in late 80's.
Nebraska	X				X				No	
Nevada	X								No	
New Hamp.		X	X	X	X	X			Yes	
New Jersey	X								Yes	
New Mexico	X	X	X	X		X			Yes	
New York	X		X	X	X	X			Yes	
North Car.									--	Stopped using L.O. in late 80's. Not using sealers. Previously limited experiments with silanes.

TABLE A-4 Continued

Highway Agency	Applications: Decks	Beams	Piers; Caps	Parapets	Median Barriers	Abutments	Sidewalks	Curb & Gutter	Approved Product List	Remarks
North Dak.	X								Yes	Extensive use of L.O.; silane use experimental to date.
Ohio		X	X	X		X			Yes	
Oklahoma	X		X	X		X			Yes	
Oregon	X	X	X	X		X			Yes	Experimented with L.O.--results not good.
Pennsylvania	X		X		X				Yes	
Rhode Island	X			X		X			Yes	
South Car.	X								Yes	No longer use linseed oil.
South Dak.	X								Yes	Linseed oil only--use L.O. emulsion curing compounds.
Tennessee	X								No	
Texas	X								No	
Utah		X	X	X		X			Yes	
Vermont			X	X	X	X			No	Extensive use of L.O. Expermented with many others in mid-80's--poor performance.
Virginia	X			X		X			Yes	
Washington	X	X	X						No	
West Virginia	X	X		X		X			Yes	
Wisconsin	X			X		X			Yes	
Wyoming	X								Yes	
Alberta	X	X	X	X		X			Yes	
Brit. Col.				X					Yes	
Manitoba	X							X	No	
New Bruns.	X			X		X			No	
Newfoundland	X			X		X		X	No	Only experimental use to date.
Nova Scotia	X				X				--	Have not used any penetrating sealers on PCC in the last 5 or 6 years.
Ontario	X	X			X				Yes	
Quebec			X	X	X	X			Yes	
Saskatch.	X			X	X	X			Yes	Uses Alberta approved product list.
Yukon Ter.	X			X		X			No	

TABLE A-5
DOT QUESTIONNAIRE—SUMMARY OF RESPONSES: SEALER QUALIFICATION AND ACCEPTANCE TESTING

Highway Agency	Qualification						Testing Procedures Used for Sealer Evaluation and Acceptance												
	Presc-ription	Testing: Internal	Testing: External	Vendor Data	Other Data	None	Absorp-tion	Cl ion Pene-tration	Water Vapor Permeability	Sealer Penetration Depth	Rapid Chloride Permeability	Impressed Current	Corrosion Potential of Rebar	Concrete Scaling Resistance	Freeze/ Thaw Durability	Skid Resistance	Long-Term Field Performance	Specification For Linseed Oil
Alabama						X												
Arkansas	X																	X
California		X		X			X	X	X									
Colorado	X					X												
Connecticut				X		X												
Delaware				X		X												
Dist. of Co.	X					X												
Florida		X		X								X						
Georgia		X		X			X	X	X		X							
Idaho		X	X				X	X	X	X						X		
Illinois				X			X	X	X					X				
Indiana			X	X				X					X				X	
Iowa		X						X										
Kansas						X												
Kentucky				X		X												
Louisiana						X												
Maine				X	X		X	X								X		
Maryland		X																X
Massachusetts		X					X	X	X									
Michigan		X	X					X		X								
Minnesota	X																X	
Mississippi						X												
Missouri		X					X	X						X				
Montana		X	X			X												
Nebraska	X							X										
Nevada							X	X										
New Hampshire	X		X			X	X	X	X									
New Jersey	X	X					X											
New Mexico		X		X			X	X	X	X								
New York		X					X	X	X									
North Carolina					X													
North Dakota		X					X	X	X	X								
Ohio				X		X												

TABLE A-5 Continued

Highway Agency	Qualification: Presc-ription	Qualification: Testing Internal	Qualification: Testing External	Qualification: Vendor Data	Qualification: Other Data	Testing Procedures Used for Sealer Evaluation and Acceptance: None	Absorp-tion	Cl ion Pene-tration	Water Vapor Permeability	Sealer Penetration Depth	Rapid Chloride Permeability	Impressed Current	Corrosion Potential of Rebar	Concrete Scaling Resistance	Freeze/ Thaw Durability	Skid Resistance	Long-Term Field Performance	Specification For Linseed Oil
Oklahoma		X					X	X	X	X								
Oregon		X	X	X	X		X	X	X									
Pennsylvania		X						X										
Rhode Island		X					X	X	X						X			
South Carolina		X				X	X	X										
South Dakota		X																X
Tennessee		X						X										
Texas	X					X												
Utah	X	X	X	X											X			
Vermont		X					X	X							X			
Virginia		X									X				X			
Washington		X		X				X			X							
West Virginia				X		X												
Wisconsin				X								X		X				
Wyoming	X	X		X			X		X	X								
Alberta			X	X			X		X	(also, solids content, spectrographic signature, alkali resist.)								
Brit. Columbia	X		X			X	X	X	X									
Manitoba	X			X		X												
New Brunswick	X	X			X													
Newfoundland	X					X												
Nova Scotia						X												
Ontario		X	X				X							X				
Quebec		X					X	X	X									
Saskatch.					X	X												
Yukon Ter.					X	X												

TABLE A-6
DOT QUESTIONNAIRE—SUMMARY OF RESPONSES: SEALER FIELD TESTS

Highway Agency	Field Tests: None	Yes (unspecified)	Cores	Chloride Sampling	Sealer Penetration Depth	Electrical Resistance	Water Flood	Visual Observation: Scaling Ratings
Alabama								
Arkansas	X							
California	X							
Colorado	X							
Connecticut	X							
Delaware	X							
Dist. of Co.	X							
Florida				X				
Georgia				X				
Idaho	X							
Illinois	X							
Indiana		X						
Iowa	X							
Kansas								
Kentucky	X							
Louisiana				X				
Maine	X							
Maryland	X							
Massachusetts		X						
Michigan	X							
Minnesota				X				
Mississippi								
Missouri	X							
Montana					X			
Nebraska				X				
Nevada				X				
New Hampshire	X							
New Jersey								X
New Mexico	X							
New York	X							

Highway Agency	Field Tests: None	Yes (unspecified)	Cores	Chloride Sampling	Sealer Penetration Depth	Electrical Resistance	Water Flood	Visual Observation: Scaling Ratings
North Carolina								
North Dakota		X						
Ohio	X							
Oklahoma					X		X	
Oregon				X				
Pennsylvania	X							
Rhode Island					X			
South Carolina	X							
South Dakota		X						
Tennessee	X							
Texas	X							
Utah	X							
Vermont				X				
Virginia			X					
Washington				X		X		X
West Virginia		X						
Wisconsin	X							
Wyoming		X						
Alberta	X							
Brit. Columbia		X						
Manitoba	X							
New Brunswick							X	
Newfoundland		X						
Nova Scotia								
Ontario	X							
Quebec	X							
Saskatch.	X							
Yukon Ter.	X							

TABLE A-7
DOT QUESTIONNAIRE—SUMMARY OF RESPONSES: SEALER PROBLEMS

Highway Agency	Sealer Selection	Sealer Approval	Sealer Application	Sealer Performance
Alabama	N/A	N/A	N/A	N/A
Arkansas	None	None	None	None
California	Environmental & air quality restrictions limit choices.	Lack of good, consistent sealer penetration test.	Yes*	Need satisfactory in-situ performance test.
Colorado	None	None	Yes*	Lack of tests for reapplication.
Connecticut	None	None	None	None
Delaware	Don't know what needed--difficult to reject.	N/R	None	No follow-up--performance unknown.
Dist. of Co.	None	None	None	None
Florida	None	None	Vague mfg. instructions regarding concrete cond.	None
Georgia	None	None	None	None
Idaho	None	None	None	Nonuniform sealer penetration.
Illinois	None	None	None	None
Indiana	None	Vendors reluctant to have testing per NCHRP244-Series IV.	Probs. regarding 28 day cure & temp./weather requirements.	Epoxies discolor from UV exposure.
Iowa	None	None	None	None
Kansas	N/A	N/A	N/A	N/A
Kentucky	Product information is limited.	Product information is limited.	None	None
Louisiana	None	None	None	Yes*
Maine	None	None	None	None
Maryland	N/A	N/A	N/A	N/A
Massachusetts	None	None	None	None
Michigan	None	None	None	Difficult to evaluate.
Minnesota	Need prequalifying procedure for field testing.	Prefer to base on field experience--time consuming.	Runoff on dense concrete bridge deck overlays.	Doesn't always meet mfgrs. claims.
Mississippi	N/A	N/A	N/A	N/A
Missouri	None	Difficulty quantifying sealer penetration.	None	None
Montana	Yes, type of silanes to specify.	None	Mfgrs. recomm. not uniform. Temp./visc. relat. unclear.	Don't have an extensive data base.
Nebraska	None	None	Yes*	None
Nevada	None	None	MMA appl. difficult due to odor & fire hazard.	MMA delaminated after 1 yr. on pvmt. No prob. on br.
New Hampshire	None	None	None	None
New Jersey	N/R	N/R	None	None
New Mexico	Current spec does not permit siloxane--vendor pressure.	None	None	None
New York	None	Presently hampered by lack of adequate lab facilities.	None--well controlled by mfgr. instr. & NY Spec. 18559.17	None

N/A = Not Applicable; N/R = No Response; * = No Elaboration

TABLE A-7 Continued

Highway Agency	Sealer Selection	Sealer Approval	Sealer Application	Sealer Performance
North Carolina	N/A	N/A	N/A	N/A
North Dakota	None	None	None	None
Ohio	None	None	None	Epoxies chalk & fade due to UV exposure.
Oklahoma	None	Long term testing req'd. Accuracy is suspect.	Deck prep.; conc. moist. content; weather; uniformity.	Uniform penetration & moist. resist. difficult to obtain.
Oregon	None	None	None	None
Pennsylvania	None	None	None	None
Rhode Island	None	Freeze-thaw failure & chloride intrusion.	None	None
South Carolina	Contractors try to use mat'ls that are not approved.	Suppliers don't understand specs. Lack of independ. lab tests.	Cleaning the concrete is a problem.	No follow-up to verify. Sealers are usually not reapplied.
South Dakota	N/R	N/R	Yes*	None
Tennessee	N/R	N/R	N/R	N/R
Texas	None	None	None	None
Utah	Current selection based on past performance only.	Need test procedure & performance spec.--working on.	None reported--done per mfgr. instructions.	None
Vermont	None	None	None	In gen'l, sealers have not performed well in lab or field.
Virginia	None	None	Yes*	Yes*
Washington	None-used NCHRP 244 Report in the past.	None	Silane not visible--difficult to verify coverage.	One epoxy weathered extensively; one silane not effective.
West Virginia	None	None	None	None
Wisconsin	None	Lack of assurance regarding penetration and skid res.	Yes*	None
Wyoming	Type that penetrates best? Effect of molecule size?	How long is sealer effective?	When is it useful to apply sealers and when too late?	Limited data to date indicates sealers not effective.
Alberta	None	None	None	None
Brit. Columbia	None	None	Probs. meeting restrictive application spec.	None can resist abrasion on traffic surf. Silanes cannot span cracks.
Manitoba	None	None	None	None
New Brunswick	N/R	N/R	None	Yes*
Newfoundland	None	None	None	Not long enough since application.
Nova Scotia	N/A	N/A	N/A	N/A
Ontario	None	None	Improper surf. prep. and application; inexperience.	Where properly applied, have performed satisfactorily.
Quebec	N/R	N/R	Yes*	N/R
Saskatch.	Rely on Alberta test data.	Rely on Alberta test data.	None	Not assessed to date.
Yukon Territory	N/R	N/R	Unknown	Unknown

N/A = Not Applicable; N/R = No Response; * = No Elaboration

TABLE A-8
DOT QUESTIONNAIRE—SUMMARY OF RESPONSES: WORKER SAFETY AND ENVIRONMENTAL PROTECTION

Highway Agency	Requirements Regarding Worker Health or Safety	Requirements Relative to Environmental Protection
Alabama	N/A	N/A
Arkansas	None	None
California	Must comply with OSHA requirements (CalTrans does not provide enforcement)	Must comply with state/local regulations (CalTrans does not provide enforcement)
Colorado	None	None
Connecticut	None	None
Delaware	None	None
Dist. of Co.	None	None
Florida	None	None
Georgia	Respiratory protection if necessary. Gloves, hard hat, and vest req'd. GA enforces all OSHA regulations.	None
Idaho	None	None
Illinois	None	None
Indiana	Yes; per std. specs., Mfg. Rep. responsible to instruct workmen. Also require use of proper gear.	Yes; std. specs. prohibit discharge into or near water courses.
Iowa	Material Safety Data Sheets required for all chemical products.	Department of Natural Resource rules are followed.
Kansas	N/A	N/A
Kentucky	Must follow manufacturer's recommendations	None
Louisiana	N/R	N/R
Maine	N/R	N/R
Maryland	None	None
Massachusetts	None	None by Mass. Hwy. Dept.; not known if enforced by other agencies.
Michigan	None	None
Minnesota	Material Safety Data Sheets must be in hand before any sealer can be used.	None
Mississippi	N/A	N/A
Missouri	None–use only linseed oil.	None
Montana	Contractor responsibility to handle in compliance with OSHA regulations.	Spillages & vapor release subject to state health regulations–must be reported to Env. Hlth. Dept.
Nebraska	None	None
Nevada	Contractor must follow mfgr. recommend. Mfg. tech. rep. must be on site when applying MMA.	Mfgrs. recommendations must be followed
New Hampshire	None	None
New Jersey	N/R	N/R
New Mexico	None	None

N/A = Not Applicable; N/R = No Response

TABLE A-8 Continued

Highway Agency	Requirements Regarding Worker Health or Safety	Requirements Relative to Environmental Protection
New York	Must comply with OSHA Regs. MSDS's & NYDOT Engineering Instructions 92-71 & 92-33.	Handle in accordance with MSDS's; all fed., state, & local regs. must be observed. Pollution prot. for air, water, soil.
North Carolina	N/A	N/A
North Dakota	None	None
Ohio	None	None
Oklahoma	None	None
Oregon	As required under OSHA	Approval of Environmental Section
Pennsylvania	Enforce safety precautions provided by mfgr.	Impose reasonable controls where necessary.
Rhode Island	None	Do not allow overspray or spills into water courses.
South Carolina	Contractor must follow mfgr. recommendations.	Contractors req'd to follow all federal and local guidelines.
South Dakota	N/R	N/R
Tennessee	None	None
Texas	None	None
Utah	Follow mfgrs. instruction in detail.	In accordance with state environmental procedures & policy.
Vermont	None	None
Virginia	Contractors urged to follow mfgrs. recommendations.	None
Washington	Follow mfgrs. suggested procedures and any local, state, & fed. requirements.	Follow mfgrs. suggested procedures and any local, state, and fed. requirements.
West Virginia	None	None
Wisconsin	As directed or mandated by the mfgr.	Disposal at licensed site only.
Wyoming	Follow MSDS guidelines.	None
Alberta	N/R	N/R
Brit. Columbia	Require workers to wear protective clothing.	Do not allow spillage or discharge directly to water courses.
Manitoba	None	None
New Brunswick	N/R	N/R
Newfoundland	In general with regard to ventilation and chemical substances.	Disposal into water courses prohibited. No specific regs.
Nova Scotia	N/R	N/R
Ontario	Follow mfgrs. requirements.	Enclosed protection from overspray over water courses. Disposal in accord with Envr. Regs.
Quebec	N/R	N/R
Saskatch.	Crews provided with MSDS's.	Crews provided with MSDS's.
Yukon Ter.	N/R	N/R

N/A = Not Applicable; N/R = No Response

APPENDIX B

SEALER MANUFACTURERS' QUESTIONNAIRE AND REPLY SUMMARY TABULATIONS

The identities of 169 sealer manufacturers were compiled from a variety of sources. Questionnaire forms were mailed to 114 of them. Thirty were returned as "undeliverable." Responses were received from 23 of the remaining 84. Despite the rather low response level, the generic types were well covered and the detail of the responses was generally good.

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM
NCHRP Project 20-5/Topic 24-12
"Sealers for Portland Cement Concrete Highway Facilities"

QUESTIONNAIRE FOR SEALER MANUFACTURERS

NOTE: It is **NOT** necessary that respondents identify their firms nor their products by trade name. The objective is to obtain general information on generic classes of concrete sealers.

		Product #1	Product #2	Product #3
1.	**Generic Chemical Classification**			
	(check one): Acrylic	______	______	______
	Chlorinated Rubber	______	______	______
	Epoxy (water-dispersed)	______	______	______
	Epoxy (solvent-dispersed)	______	______	______
	Latex	______	______	______
	Linseed Oil	______	______	______
	Mineral Gum	______	______	______
	Polyester	______	______	______
	Silane	______	______	______
	Silicate	______	______	______
	Fluosilicate	______	______	______
	Siloxane	______	______	______
	Stearate	______	______	______
	Urethane	______	______	______
	If none of the above, describe:	______	______	______
		______	______	______
2.	**Carrier or diluent used** (if applicable)			
	Type:	______	______	______
	Vol. %:	______	______	______
3.	**Percent solids** (if applicable) :	______	______	______
4.	**Cost** ($/gal in 1,000 gal lots F.O.B. Plant) :	$ ____ /gal	$ ____ /gal	$ ____ /gal

5. **Recommended Application Rate**

Sq.ft./gal./coat:	____ sf/gal	____ sf/gal	____ sf/gal
Number of coats:	________	________	________

6. **Recommended Application Method**

(check all that apply):

Squeegee	________	________	________
Roller	________	________	________
Broom or Brush	________	________	________
Spray (air)	________	________	________
Spray (airless)	________	________	________
Other(s)—Please List	________	________	________
	________	________	________

7. **Product Safety Data**

If Material Safety Data Sheets (such as OSHA-20 form or other forms containing the information required by the Hazard Communication Standard) are available for your products, please attach copies marked with the above product identification numbers (product names may be deleted).

PLEASE RETURN THE COMPLETED QUESTIONNAIRE WITH ATTACHED MATERIAL SAFETY DATA SHEETS TO THE NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM'S CONSULTANT ON THIS PROJECT:

Dr. Philip D. Cady, P.E.
P.O. Box 158
Lemont, PA 16851-0158

ANY QUESTIONS REGARDING THE QUESTIONNAIRE SHOULD ALSO BE DIRECTED TO DR. CADY AT THE ABOVE ADDRESS OR BY PHONE (814)238-3215.

PLEASE RETURN COMPLETED QUESTIONNAIRE BY DECEMBER 31, 1992

TABLE B-1
SEALER MANUFACTURER'S QUESTIONNAIRE—SUMMARY OF RESPONSES, MATERIAL COSTS, APPLICATION RATES AND METHODS

Sealer Type	Diluent	% Active[1] Avg.	% Active[1] Range	Cost, $/gal[2] Avg.	Cost, $/gal[2] Range	Application Rate s.f./gal/coat Avg.	Application Rate s.f./gal/coat Range	No. of Coats	Application Method[3] Squeegee	Roller	Broom Brush	Spray Air	Spray Air less
Acrylic	None	100	100	32.00	32.00	160	160	1		X	X		X
	Xylene	21	21	18.00	18.00	300	300	2		X			X
	Water	21	21	16.00	16.00	300	300	2		X			X
Acrilic-Siloxane	Min. Spirits	13	13	18.00	18.00	125	125	1					X
Mix	Water	8	8	9.00	9.00	150	100-200	1		X			X
Linseed Oil	Min. Spirits	50	50	2.86	2.86	360	360	2				X	X
Epoxy	Xylene	50	15-75	16.00	15.00-17.40	160	75-300	2		X	X	X	X
	Toluene	51	50-58	23.00	20.00-26.00	144	90-200	2		X		X	
	Water	48	35-70	32.00	29.75-34.00	160	125-200	2		X	X		X
Silane	Isopropanol	20	20	14.25	14.25	125	125	1		X	X		X
		40	40	21.20	19.65-23.96	140	125-175	1		X		X	X
	Min. Spirits	20	20	13.95	13.95	150	150	1		X	X	X	X
		40	40	18.80	18.80	150	150	1		X	X	X	X
	Water	20	20	14.75	14.25-15.25	138	125-150	1		X	X		X
		40	40	19.73	19.65-19.80	150	150	1		X	X		X
Siloxane	Min. Spirits	14	7-20	22.00	14.75-30.00	175	80-400	1		X		X	X
	Water	17	17	18.00	18.00	125	125	1	X	X	X		X
		20	20	29.19	29.19	125	125	1	X	X		X	
		65	65	33.00	31.00-34.00	125	125	1				X	X
Silane-Siloxane Mix	Min. Spirits	15	15	17.00	17.00	125	125	1	X	X	X		X
Silicates	Water	--	--	18.00	5.10-30.00	190	175-200	2	X	X	X	X	X
Urethane	Xylene	51	48-57	24.00	24.00	190	125-250	2		X		X	X

Notes: (1) By weight.
(2) In 1,000 gal lots, F.O.B. plant.
(3) Specified by majority of manufacturers.

TABLE B-2
SEALER MANUFACTURER'S QUESTIONNAIRE—SUMMARY OF RESPONSES: TEST AND PERFORMANCE DATA (AVERAGE VALUES)

Sealer Type	Acrylic-Siloxane	Epoxy			Silane				Siloxane		Siloxane	Silane/Silicate
Diluent	Mineral Spirits	Xylene	Toluene	Water	Isopropanol	Methanol	Mineral Spirits	Water	Mineral Spirits	Water	Mineral Spirits	Water
NCHRP 244												
Series II % Reduction of Water Absorption	81		91	94	86	68	82	79	82	79	87	
% Reduction of Chloride Absorption	86	97	94	94	90		86	88	86	84	96	
Series IV (Southern Exposure):												
% Red. Cl- Abs.	100		99	94	99	99	100	99	96	90		97
Alberta BT-001 @ 45% Relative Moisture												
Initial Performance, %					89			89				
Post-Abrasion Performance, %					89			88				
Alkali Resistance, %					88			87				
ASTM C642 - Water Absorption, %												
48-hour				0.02	0.28	0.46		0.42				
50-day				0.80	1.37			1.68	1.40			
Avg. Sealer Penetration Depth, inches	0.31				0.26	0.38		0.17	0.41	0.09		
AASHTO T159/T260: Chloride Ion Content												
1/16 - 1/2 in. depth, lb/cy			3.10		0.15	0.18	0.83	0.33	4.98			
1/2 - 1 in. depth, lb/cy			0.33		0.07	0.00	0.13	0.00	3.70			
OHD-L-35: Vapor Permeability Moist. Loss, %				101	>100		102					
ASTM C672 - Scaling Rating												
@ 50 cycles	0	0			0+		0		0	0	0	1
@ 100 cycles				0	0	0+		0		0+		
@ 150 cycles	1-									1		
ASTM D1653 - Moist. Vapor Transmission Rate, g/sf/24h @ 75F								36.6				
ASTM E96 (Procedure B) - Water Vapor Transmission, Perms							2.03		2.52			

TABLE B-3
SEALER MANUFACTURERS' QUESTIONNAIRE—SUMMARY OF RESPONSES: TEST AND PERFORMANCE DATA (VARIABILITY OF RESULTS)

Sealer Type	Silane (Solvent Dispersed:Isopropanol)			Silane (Water Dispersed)			Siloxane (Solvent Dispersed: Mineral Spirits)		
Statistic	Mean	Range	n	Mean	Range	n	Mean	Range	n
NCHRP 244									
Series II % Reduction of Water Absorption	86	77-89.3	9	79	75-83	4	82	75-85	3
% Reduction of Chloride Absorption	90	82-97.6	9	88	83-95	3	86	75-92	3
Series IV (Southern Exposure):									
% Red. Cl Absorption	99	97-100	9	99	99	2	96	91-100	5
Alberta BT-001 @ 45% Relative Moisture									
Initial Performance, %	89	88.7-88.9	2	89	85.6-91.3	3			
Post-Abrasion Performance, %	89	89.2	1	88	87.8-87.9	2			
Alkali Resistance, %	88	88.3	1	87	84.9-89.7	2			
ASTM C642 - Water Absorption, %									
48-hour	0.28	0.0-0.48	4	0.42	0.30-0.53	3			
50-day	1.37	0.8-2.77	4	1.68	1.20-2.38	3	1.40	1.40	1
Avg. Sealer Penetration Depth, inches	0.26	0.14-0.5	6	0.17	0.13-0.24	3	0.41	0.13-0.75	
AASHTO T259/T260: Chloride Ion Content									
1/16 - 1/2 in. depth, lb/cy	0.15	0.1-0.2	4	0.33	0.19-0.52	3	4.98	1.15-8.8	2
1/2 - 1 in. depth, lb/cy	0.07	0.00-0.16	4	0.00	0.00	2	3.70	0.20-5.2	2
OHD-L-35: Vapor Permeability Moist. Loss, %	101	100.4-102	4	102	100-104	3			
ASTM C672 - Scaling Rating									
@50 cycles	0^{+}	$0\text{-}1^{-}$	2				0	0	4
@ 100 cycles	0	$0\text{-}0^{+}$	5	0	0	2			
@ 150 cycles									
ASTM D1653 - Moist. Vapor Transmission Rate, g/sf/24h @ 75F				36.6	36.6	1			
ASTM 96 (Procedure B) - Water Vapor Transmission, Perms							2.52	2.52	1

TABLE B-4
SEALER MANUFACTURER'S QUESTIONNAIRE—SUMMARY OF RESPONSES: HAZARDOUS FEATURES (1)

			HMIS Hazard Rating(2)			Flash Point	Explosive Limits(%)		Possibly Hazardous Ingredients					
										Exposure Limits(3), ppm			Inhalation	Ingestion
										OSHA	ACGIH		(Rat),	(Rat)
Sealer Type	Diluent	Component	Health	Fire	Reactivity	°F	Lower	Upper	Material	PEL	TLV	STEL	ppm	g/kg
Acrylic	None		2	3	2	52.7	2.1	12.5	methyl methacrylate monomer	100	100		3,750	9.4
	Xylene		2	3	0	80	1.0	7.0	2-ethylhexyl acrylate					6.5
									xylene	100	100	150		
									benzoyl peroxide		5mg/m³			
									cumene		50			
									cobalt octoale		0.1mg/m³			
									manganese carboxylate		5mg/m³			
Acrylic-Siloxane Mix	Min. Spirits	(See "Acrylic-None" and "Siloxane-Mineral Spirits")												
	Water	(See "Acrylic-None" and "Siloxane-Water")												
Linseed Oil	Min. Spirits					100	1	5	M.S. (aliphatic petroleum distilate)	100	100			
									linseed oil	500	100			
Epoxy	Xylene	Resin	2	3	0	64-88	1	7	xylene	100	100	150		
		Hardener	2-3	3	0				toluene	100	100	150	4,000	5.0
	Toluene	Resin	2-3	3	0-1	43-45	1-1.4	6.9-7	bisphelol A diglycidyl ether					11.4
		Hardener	2-3	3	0-1				epoxy					>4.0
	Water	Resin	2	1	0	350-	none	none	polyamide resin					6.7
		Hardener	1-2	0-1	0-1	375			alkyl glycidyl ether				1,030	2.0
Silane	Isopropanol		1-3	2-3	1	53-78	2-2.5	12-12.8	isopropanol	400	400	500		5.84
	Methanol		1	3	0	53-111	not determ.		methanol	200	200	250		
	Min. Spirits		2	2	1	105	0.9-1	6-6.1	mineral spirits	100	100			
									iso octyltrimethoxy silane	200	200		16,000	5.045
	Water			2		none	none	none						

TABLE B-4 Continued

			HMIS Hazard Rating[2]			Flash Point	Explosive Limits(%)		Possibly Hazardous Ingredients					
										Exposure Limits[3], ppm			Inhalation	Ingestion
										OSHA	ACGIH		(Rat),	(Rat)
Sealer Type	Diluent	Component	Health	Fire	Reactivity	°F	Lower	Upper	Material	PEL	TLV	STEL	ppm	g/kg
Siloxane	Isopropanol		1	3	0	78	2.0	12.0	isopropanol	400	400	500		5.84
	Min. Spirits		1-2	1-2	0-1	52-110	0.7-1.1	5-6.9	mineral spirits	100	100			
	Water		2	0	0	none	none	none	methanol (released upon hydrolysis)	200	200	250		
									ethanol (released upon hydrolysis)	1000	1000			
									ethyl silicate	100	10			
									acetic acid	10	10			
Silane-Siloxane Mix		Min. Spirits		no data			109	not determ.		mineral spirits		100	100	
									silane-siloxane mix					7.5
Silicates	Water		1	0	0	none	none	none	none					
Urethane	Xylene/ Toluene		2	3	1	75-81	1.1-1.24	12.7	aromatic petroleum solvent	100	100			
									xylene	100	100	150		
									toluene	100	100	150	4,000	5.0
									methyl isobutyl ketone	100	50			
									free aromatic diisocyanate	0.02	0.02			

Notes: [1]Data compiled from Material Safety Data Sheets.
[2]0 = insignificant; 1 = slight; 2 = moderate; 3 = high; 4 = extreme.
[3]PEL = permissible exposure level; TLV = threshold limit value; STEL = short-term exposure limit. Units other than ppm shown.

TABLE B-5
SEALER MANUFACTURER'S QUESTIONNAIRE—SUMMARY OF RESPONSES: FIRE FIGHTING STRATEGY AND HAZARDS [1]

		Extinguishing Modes						Special Fire Fighting Procedures				Unusual Fire & Expl. Hazards				
Sealer Type	Diluent	Water Fog	Dry Chemical	Foam	Alcohol Foam	CO_2	Not Applicable	Self Contain Breathing Apparatus	Full Bunker Gear w/ Facepiece	Cool Containers w/Water Spray	None	Toxic Decomposition Products	Dense Vapors (Flash Back)	Explosive Vapors	Ignit. by Strong Oxidizers	None Known
Acrylic	None	X	X	X	X	X		X	X	X			X		X	
	Xylene	X	X	X		X		X		X			X	X	X	
	Water						X				X					X
Acrylic-							X				X					X
Siloxane	Water						X				X					X
Linseed Oil	Min.Sp.			X		X		X	X	X						X
Epoxy	Xylene	X	X	X		X		X	X	X		X		X		
	Toluene	X	X	X		X		X	X	X		X	X			
	Water						X			X	X					X
Silane	Isoprop.	X	X	X	X	X		X	X	X			X	X		
	Min.Sp.	X	X	X	X	X		X	X	X						X
	Meth.	X	X	X	X	X		X	X	X			X	X		
	Water	X	X	X		X		X	X							X
Siloxane	Isoprop.		X	X		X		X	X					X		
	Min.Sp.	X	X	X	X	X		X	X	X			X			
	Water	X	X	X		X		X		X						X
Silane-Siloxane	Min.Sp.		X	X		X					X			X		
Silicates	Water						X				X					X
Urethane	Xyl./M.S.	X	X	X	X	X		X		X		X				

Notes: [1]Data compiled from Material Safety Data Sheets.

TABLE B-6
SEALER MANUFACTURER'S QUESTIONNAIRE—SUMMARY OF RESPONSES: PRODUCT REACTIVITY [1]

Sealer Type	Acrylic			Acrylic Siloxane	Linseed Oil	Epoxy			Silane				Siloxane			Silane/ Siloxane	Silicate	Urethane
Diluent	None	Xylene	Water	Water	Mineral Spirits	Xylene	Toluene	Water	Isopropanol	Methanol	Mineral Spirits	Water	Isopropanol	Mineral Spirits	Water	Mineral Spirits	Water	Xylene/ Toluene
STABILITY																		
Stable (Yes or No)	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Conditions to Avoid:																		
High Temperature	X	X				X		X	X	X	X			X	X	X		X
Moisture; Humidity										X				X		X		X
Ignition Sources	X	X				X			X	X	X	X	X	X				
Contamination								X										
Electrostatic	X	X																
Aging	X							X										
Sunlight								X										
INCOMPATIBILITY																		
Materials to Avoid:																		
Acids	X					X	X	X	X	X	X	X		X				X
Bases						X	X					X						X
Oxidizing Agents	X	X			X	X	X	X	X	X	X	X	X	X	X			
Reducing Agents	X								X						X			
Alcohols																		X
Aldehydes									X	X								
Alkalies	X								X	X	X			X				
Aluminum									X	X			X					
Amides							X											
Amines	X						X	X		X	X	X						X
Ammonia										X								
Azo Compounds	X																	
Combustible Mat'ls	X																	
Halogens									X	X			X					
Heavy Metal Ions	X																	
Ionic Solutions								X										
Isocyannates							X											X
Mercaptans						X	X											

[1]Data compiled from Material Safety Data Sheets.

TABLE B-6 Continued

Sealer Type	Acrylic			Acrylic Siloxane	Linseed Oil	Epoxy			Silane				Siloxane			Silane/ Siloxane	Silicate	Urethane
Diluent	None	Xylene	Water	Water	Mineral Spirits	Xylene	Toluene	Water	Isopropanol	Methanol	Mineral Spirits	Water	Isopropanol	Mineral Spirits	Water	Mineral Spirits	Water	Xylene/ Toluene
INCOMPATIBILITY																		
Materials to Avoid:(cont'd)																		
Natural Rubber						X												
Organic Solvents								X										
Organometallic Comp.													X					X
Peroxides	X						X		X				X		X			
Phosphorous																		X
Radical Sources	X																	
Surfactants																		X
HAZARDOUS DECOMPOSITION PRODUCTS																		
CO	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X		X
CO_2	X	X	X	X		X	X	X	X	X	X	X	X	X	X	X		X
HCN			X	X														X
NH_3															X			
NO_x						X	X	X	X									X
SiO_2									X	X		X			X	X		
Unidentified Organics		X	X	X			X		X	X				X	X			
Aldehydes		X				X	X	X										
Acidic Vapors							X											
Biphenyl	X																	
Methanol									X					X		X		
Ethanol									X									
Smoke	X	X			X									X				

TABLE B-7
SEALER MANUFACTURER'S QUESTIONNAIRE—SUMMARY OF RESPONSES: PERSONNEL HEALTH HAZARDS [1]

Sealer Type	Acrylic			Acrylic Siloxane	Linseed Oil	Epoxy			Silane				Siloxane			Silane/ Siloxane	Silicate	Urethane
Diluent	None	Xylene	Water	Water	Mineral Spirits	Xylene	Toluene	Water	Isopropanol	Methanol	Mineral Spirits	Water	Isopropanol	Mineral Spirits	Water	Mineral Spirits	Water	Xylene/ Toluene
HEALTH HAZARDS																N		
Skin Irritant	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	O	X	X
Eye Irritant	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X		X	X
Respiratory Irritant	X	X			X	X	X	X	X		X	X		X	X	D		X
Gastrointestinal Irritant		X	X	X												A	X	
Cent. Nervous																T		
System Depressant		X			X		X		X	X	X			X		A		X
Toxic	X																	
Carcinogenic	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No
SYMPTOMS OF EXPOSURE																		
Skin Burns							X	X	X	X	X	X	X	X	X			X
Dermatitis; Itching	X	X				X	X	X	X	X	X	X	X	X	X	N		X
Conjunctivitis							X		X	X	X		X	X		O		X
Blurred Vision												X						
Respiratory Distress							X							X		D		
Nose/Throat Irritation		X						X	X							A		X
Diarrhea									X						X	T		
Nausea	X	X			X	X	X	X	X		X	X		X	X	A	X	X
Headache	X					X	X	X	X		X	X	X	X	X		X	X
Drowsiness									X				X					
Dizziness		X			X	X	X		X		X			X				X
MED. COND. AGGRAVATED																		
Allergies						X		X										X
Eczema						X		X										X
Pre-Existing Skin																		
Disorders	X	X				X	X	X	X					X				X
Pre-Existing Eye																		
Disorders		X					X		X					X				
Pre-Existing Respir.																		
Disorders		X			X	X	X	X	X		X	X	X	X				
Dermatitis						X		X	X		X	X			X			
Asthma									X		X				X			
CNS Depression							X											
Narcosis							X											
Liver Functions		X					X								X			
Kidney Functions		X					X								X			

[1]Data compiled from Material Safety Data Sheets.

TABLE B-8
SEALER MANUFACTURER'S QUESTIONNAIRE—SUMMARY OF RESPONSES: PRECAUTIONS FOR HANDLING, STORAGE, AND USE [1]

Sealer Type	Acrylic			Acrylic Siloxane	Linseed Oil	Epoxy			Silane				Siloxane			Silane/ Siloxane	Silicate	Urethane
Diluent	None	Xylene	Water	Water	Mineral Spirits	Xylene	Toluene	Water	Isopropanol	Methanol	Mineral Spirits	Water	Isopropanol	Mineral Spirits	Water	Mineral Spirits	Water	Xylene/ Toluene
SPILLS																		
Remove Ignition Sources	X	X			X	X	X		X	X	X	X	X	X	X	X		X
Ventilate Area	X	X				X	X		X						X			X
Dike-Prevent Runoff to Sewers & Surface Waters	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Pump or Absorb w/Fillers and Place in Drums	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Fush w/Water	X					X	X		X	X			X	X	X		X	X
WASTE DISPOSAL																		
Per Local, State, Fed. Regs.	X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X
Approved Landfill	X					X			X	X	X	X		X	X			X
Incinerate	X					X			X		X	X			X			
Polymerize	X																	
Flush Into Sanitary Sewer																	X	
Evap. Volatiles in Hood									X					X				
HANDLING & STORAGE																		
Store in Cool, Dry Location	X	X			X	X	X	X	X	X	X	X	X	X	X			X
Good Ventilation	X	X				X		X	X	X	X	X	X	X	X			
No Ignition Sources	X	X				X			X	X	X	X		X	X			X
Ground Containers	X	X					X		X									
Prohibit Freezing								X									X	
Do Not Cut, Grind Weld Cont.	X	X							X									
USE																		
Practice Good Hygiene	X	X				X		X	X	X	X	X	X	X	X		X	X
Eye Protection	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Respiratory Prot. (as needed)	X	X	X	X	X	X	X		X	X	X		X	X	X			X
Protective Gloves	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Clean Protective Clothing	X	X			X	X	X	X	X	X	X	X	X	X	X			X
Eyewash Station	X	X	X	X		X	X	X		X	X	X	X	X	X	X		
Safety Showers	X	X				X	X	X		X	X	X	X	X	X	X		
Adequate Ventilation	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X		X
Use Barrier Creme						X		X	X									X

[1]Data compiled from Material Safety Data Sheets.

APPENDIX C

PROCEDURE FOR ESTIMATION OF SERVICE LIFE (SHRP) (*116*)

The following information is presented to illustrate the steps involved in estimating sealer service life using the method recently developed under the Strategic Highway Research Program (SHRP) Project C-103. The basic tenents and theory involved are covered under "Sealer Service Life" in Chapter 3 of this synthesis.

The steps involved are as follows:

1. Estimate the field environmental effective chloride diffusion constant, D_c, using field data or tabulated reference values (e.g., Table 13 in Chapter 3).

2. Calculate the estimated average equilibrium chloride concentration level, C_o', resulting from chloride leakage through the sealed zone of the concrete surface, that is just sufficient to produce the corrosion threshold chloride content at the surface of the reinforcing steel, $C_{(x,t)}$, by the end of the expected useful life of the structure, t.

The appropriate relationship is:

$$C_o' = \frac{C_{(x,t)}}{\left[1 - \operatorname{erf}\dfrac{x}{2\sqrt{D_c t}}\right]}$$

where:

erf = the "error function" for the computed value of the argument $(x/2\sqrt{D_c t})$ (See Table C-1).

x = depth of cover of the shallowest 2.5 percent of the reinforcing steel.

3. Calculate the estimated equivalent field time, t_{eq}, which produces a chloride ion concentration $C_{(x,t)}'$ in 30 weeks of ponding untreated (control) specimens using the previously estimated field environmental effective diffusion constant, D_c, and the equilibrium chloride content, C_{0-1c}, from the 30-week ponding test, i.e., solve the following equation for t_{eq}:

$$\operatorname{erf}\left(\frac{x'}{2\sqrt{D_c t_{eq}}}\right) = 1 - \left(\frac{C'_{(x,t)}}{C_{o-1c}}\right)$$

4. Assuming linear increase in equilibrium concentration versus time, the total allowable equilibrium concentration at time t (the service life of the structure), $C_{0\text{-total}}$, equals two times the average equilibrium chloride concentration, C_o, i.e.,

$$C_{0\text{-total}} = 2\,C_o'$$

5. Calculate the average allowable equilibrium concentration, $C_{o\text{-eq}}$.

$$C_{0\text{-eq}} = C_{0\text{-total}}\left(\frac{t_{eq}}{t}\right)$$

6. Determine the laboratory leakage factor, LR, from the ratio of the equilibrium chloride concentrations (at 1.27 cm depth) in the sealed and unsealed 30-week ponding tests, i.e.,

$$LR = \left(\frac{C_{o-1s}}{C_{o-1c}}\right) 100 \qquad (\%)$$

where C_{0-1s} and C_{o-1c} are the 30-week ponding test equilibrium chloride concentration at 1.27 cm depth for the sealed and the control (unsealed) specimens, respectively.

7. Determine the allowable leakage factor, $LR_{allowed}$, as follows:

$$LR_{allowed} = \left(\frac{C_{o-eq}}{C_{o-1c}}\right) 100 \qquad (\%)$$

8. Determine the estimated life of the sealer (i.e., reapplication period), t_{sl}, from the relationship:

$$t_{sl} = t_{eq}\left(\frac{LR_{allowed}}{LR}\right)$$

<u>Example</u>

- For the bridge site in question, the estimated field environmental effective chloride diffusion constant, $D_c = 0.32$ cm^2/yr.
- The bridge field site environmental chloride equilibrium concentration, C_o, is 4.76 kg/m^3.
- The chloride corrosion threshold concentration, $C_{(x,t)} = 0.71$ kg/m^3.
- The useful service life of the structure, t = 50 years.
- The 30-week ponding test chloride equilibrium concentrations at 1.27 cm depth are:
  - —control (unsealed) specimen, $C_{o-1c} = 4.49$ kg/m^3
  - —sealed specimen, C_{o-1s} – 0.16 kg/m^3.
- The 30-week ponding chloride concentration in the control (unsealed specimen) at depth x′ = 2.54 cm, $C_{(x,t)}' = 0.70$ kg/m^3.
- The mean reinforcement cover depth is 5.08 cm with a standard deviation of 0.51 cm, giving the depth of cover for the shallowest 2.5 percent of the reinforcement, x = 4.08 cm.

1. $D_c = 0.32$ cm^2/yr

2. $$C_o' = \frac{C_{(x,t)}}{1 - \operatorname{erf}\left(\dfrac{x}{2\sqrt{D_c t}}\right)}$$

$$= \frac{0.71 \text{ kg/m}^3}{1 - \operatorname{erf}\left(\dfrac{4.08}{2\sqrt{(0.32)(50)}}\right)} = 1.508 \text{ kg/m}^3$$

3. $$\operatorname{erf}\left(\frac{x'}{2\sqrt{D_c t_{eq}}}\right) = 1 - \left(\frac{C'_{(x,t)}}{C_{o-1c}}\right)$$

$$\operatorname{erf}\left(\frac{2.54}{2\sqrt{0.32 t_{eq}}}\right) = 1 - \left(\frac{0.70}{4.49}\right) = 0.84410$$

$t_{eq} = 5.00$ yr.

4. $C_{o\text{-total}} = 2\,C_o' = (2)(1.508) = 3.016$ kg/m^3

5. $C_{o\text{-}eq} = C_{o\text{-}total}\,\frac{t_{eq}}{t} = (3.016)\left(\frac{5.00}{50}\right)$
$= 0.302\ kg/m^3$

6. $LR = \left(\frac{C_{o-1s}}{C_{o-1c}}\right) 100 = \left(\frac{0.16}{4.49}\right) 100 = 3.56\%$

7. $LR_{allowed} = \left(\frac{C_{o\text{-}eq}}{C_o}\right) 100 = \left(\frac{0.302}{4.76}\right) 100 = 6.34\%$

8. Service life of sealer, $t_{sl} = t_{eq}\left(\frac{LR_{allowed}}{LR}\right)$
$= (5.00)\left(\frac{6.34}{3.56}\right) = 8.9$ years

Therefore, if sealer is applied to the new concrete and reapplied every 9 years thereafter, in 50 years time the chloride concentration at the depth of the shallowest 2.5 percent of the reinforcing steel will reach the corrosion threshold level.

TABLE C-1
ERROR FUNCTION VALUES FOR THE ARGUMENT VALUES Y (*17*)

y	Erf y	y	Erf y	y	Erf y
0.02	0.02256	1.02	0.85084	2.02	0.99572
0.04	0.04511	1.04	0.85865	2.04	0.99609
0.06	0.06762	1.06	0.86614	2.06	0.99642
0.08	0.09008	1.08	0.87333	2.08	0.99673
0.10	0.11246	1.10	0.88021	2.10	0.99702
0.12	0.13476	1.12	0.88679	2.12	0.99728
0.14	0.15695	1.14	0.89308	2.14	0.99753
0.16	0.17901	1.16	0.89910	2.16	0.99775
0.18	0.20093	1.18	0.90484	2.18	0.99795
0.20	0.22270	1.20	0.91031	2.20	0.99814
0.22	0.24430	1.22	0.91553	2.22	0.99831
0.24	0.26570	1.24	0.92051	2.24	0.99846
0.26	0.28690	1.26	0.92524	2.26	0.99861
0.28	0.30788	1.28	0.92973	2.28	0.99874
0.30	0.32863	1.30	0.93401	2.30	0.99886
0.32	0.43913	1.32	0.93807	2.32	0.99897
0.34	0.36936	1.34	0.94191	2.34	0.99906
0.36	0.38933	1.36	0.94556	2.36	0.99915
0.38	0.40901	1.38	0.94902	2.38	0.99924
0.40	0.42839	1.40	0.95229	2.40	0.99931
0.42	0.44747	1.42	0.95538	2.42	0.99938
0.44	0.46623	1.44	0.95830	2.44	0.99944
0.46	0.48466	1.46	0.96105	2.46	0.99950
0.48	0.50275	1.48	0.96365	2.48	0.99955
0.50	0.52050	1.50	0.96611	2.50	0.99959
0.52	0.53790	1.52	0.96841	2.52	0.99963
0.54	0.55494	1.54	0.97059	2.54	0.99967
0.56	0.57162	1.56	0.97263	2.56	0.99971
0.58	0.58792	1.58	0.97455	2.58	0.99974
0.60	0.60386	1.60	0.97635	2.60	0.99976
0.62	0.61941	1.62	0.97804	2.62	0.99979
0.64	0.63459	1.64	0.97962	2.64	0.99981
0.66	0.64938	1.66	0.98110	2.66	0.99983
0.68	0.66378	1.68	0.98249	2.68	0.99985
0.70	0.67780	1.70	0.98379	2.70	0.99987
0.72	0.69143	1.72	0.98500	2.72	0.99988
0.74	0.70468	1.74	0.98613	2.74	0.99989
0.76	0.71754	1.76	0.98719	2.76	0.99991
0.78	0.73001	1.78	0.98817	2.78	0.99992
0.80	0.74210	1.80	0.98909	2.80	0.99992
0.82	0.75381	1.82	0.98994	2.82	0.99993
0.84	0.76514	1.84	0.99074	2.84	0.99994
0.86	0.77610	1.86	0.99147	2.86	0.99995
0.88	0.78669	1.88	0.99216	2.88	0.99995
0.90	0.79691	1.90	0.99279	2.90	0.99996
0.92	0.80677	1.92	0.99338	2.92	0.99996
0.94	0.81627	1.94	0.99392	2.94	0.99997
0.96	0.82542	1.96	0.99443	2.96	0.99997
0.98	0.83423	1.98	0.99489	2.98	0.99997
1.00	0.84270	2.00	0.99532	3.00	0.99998

APPENDIX D

MODEL SEALER SPECIFICATION
(COURTESY OF ALBERTA TRANSPORTATION AND UTILITIES)

GOVERNMENT OF THE PROVINCE OF ALBERTA

ALBERTA TRANSPORTATION AND UTILITIES

BRIDGE MATERIALS

B388-DECEMBER 92

SPECIFICATION FOR THE SUPPLY OF CONCRETE SEALERS

SCOPE - This specification describes the supply and packaging of concrete sealers. The approval requirements necessary prior to certification of the product for use as a concrete sealer are specified.

1.0 GENERAL

1.1 INTRODUCTION

This specification covers the supply of concrete sealer products consisting of one or two components.

The specification covers the approval requirements for certification of all concrete sealer products. The test requirements are designed to represent the service conditions the concrete sealer will encounter in the field.

The concrete surfaces to be sealed are subject to freeze-thaw cycles, exposure to deicing salt, extreme temperatures, rapid temperature changes and abrasion from traffic.

Products containing $CH_3Si(OR)_3$ have been identified as a health hazard which attacks the retina of the eyes and shall not be used in sealer products.

The current edition of the time of testing shall apply for codes and standards referred to within this specification and attached appendices.

1.2 CLASSIFICATION OF CONCRETE SEALERS

All proposed sealers shall be categorized into one of the types shown below:

Type 1 - penetrating sealers for use on traffic bearing surfaces exposed to abrasion. These sealers must not reduce the skid resistance of the wearing surface. These are divided into 2 categories depending on substrate exposure conditions:

Type 1a - penetrating sealers for application in sheltered conditions such as parkades where the deck is relatively dry, i.e. relative moisture content is a maximum of 55%. Relative moisture content is defined in BT001, "Alberta Test Procedure for Evaluation of Measuring the Vapour Transmission, Waterproofing and Hiding Power of Concrete Sealers.

Type 1b - penetrating sealers for application in outdoor conditions such as bridge decks where the deck relative moisture content is a maximum of 70%, representing 2 days drying in good drying conditions.

Type 2 - clear, film forming sealers for use on non-traffic bearing elements such as parapets, curbs, piers, abutments, and wingwalls. These are divided into 2 categories depending on the number of components:

Type 2a - one component, clear coatings suitable for use by less experienced personnel on non-traffic bearing surfaces where the concrete relative moisture content is a maximum of 70%.

Type 2b - two or more component coatings for use by approved contractors where higher degrees of waterproofing performance are required and where the concrete relative moisture content is a maximum of 70%.

Type 3 - coloured film forming sealers for use on elements highly exposed to public view where esthetics are a primary consideration. These products are for use on concrete surfaces where the relative moisture content is a maximum of 70%.

2.0 APPROVAL REQUIREMENTS

2.1 ARRANGEMENT FOR TESTING

The Supplier shall have his product tested for approval according to the requirements as outlined in the specification prior to tendering on any product order. When he has approval from the Department his product will be included on the approved product list.

The tests are to be carried out by an independent, CSA certified laboratory at the Supplier's expense.

The supplier shall supply at least the following information to the test laboratory: name and type of sealer, generic description, name of manufacturer and Alberta supplier, application instructions, including number of immersions or brushings and drying time between each, coverage rate, pot life if applicable, time of cube immersion in Type 1 sealer if applicable, and curing instructions if necessary.

The test procedures allow for up to two immersions for penetrating sealers and two brushings for other sealers.

In the event the supplier's instructions conflict with the provisions of the specifications or procedures the specifications or procedures shall govern.

The test results shall be submitted by the Supplier to:

Alberta Transportation & Utilities

Bridge Engineering Branch

3rd Floor, Twin Atria Building

4999 - 98 Avenue

Edmonton, Alberta

T6B 2X3

Attention: E. Kottke, Bridge Services Inspector

Telephone: (403)427-6911 FAX: (403)422-2902

The test report when submitted will become the property of the Department.

The Department reserves the right to publish the test information for their own or public use. The testing may take place and the results submitted at any time provided all the requirements are met. The Department will update the approval list after a review has been undertaken to ensure the specification requirements are satisfied.

2.2 LABORATORY TEST REPORT

The test results shall be submitted on the report form "Concrete Sealer Test Report" attached.

Original graphs of the spectrographic analysis showing frequency versus amplitude shall be included in the report. Two component sealers, such as epoxies, will require separate graphs for each component. Xerox or fax copies of the graphs are not acceptable.

2.3 LABORATORY DATA ACQUISITION FORM

The laboratory shall record all observations, weights and calculations on the report form "Lab Data Acquisition Form for Concrete Sealer Tests in Accordance with BT001" attached.

2.4 EVALUATION OF TEST RESULTS

The Department will base the acceptance of a product according to the results of the performance requirements in section 4.0 Qualifying Tests.

3.0 IDENTIFICATION OF SEALERS

3.1 SOLIDS CONTENT

For future purposes of quality control and verification that the sealers which will be purchased by the Department are identical to the sealers that have previously been tested and approved, all proposed sealers shall be tested for the amount of active solids content.

Solids contents for Type 1 sealers such as silanes, siloxanes, and silane/siloxane blends shall be measured using Test Procedure ASTM D5095 "Standard Test Method for Determination of Nonvolatile Content in Silanes, Siloxanes and Silane-Siloxane Blends Used in Masonry Water Repellent Treatments". The method for determining solids content for Type 2 and Type 3 sealers shall be measured using the method described in Test Procedure BT001 "Alberta Test Procedure for Measuring the Vapour Transmission, Waterproofing and Hiding Power of Concrete Sealers".

3.2 SPECTROGRAPHIC ANALYSIS

Each proposed sealer shall be subjected to an infrared spectrographic analysis test, and a graph of frequency versus amplitude shall be plotted for all sealers and submitted to the Department for approval. Two component sealers, such as epoxies, will require separate graphs for each component.

4.0 QUALIFYING TESTS

4.1 CASTING AND STORING OF CONCRETE TEST SPECIMENS

Test specimen cubes shall be cast from a typical 30 MPa concrete mix with a relatively high water cement ratio to simulate field cast bridge concrete. For the purpose of evaluating sealers, it is important that test specimens be uniform with respect to permeability, void space, surface texture and both the amount and distribution of interior moisture.

The specimens shall be made in accordance with B-390 "Specification for the Casting and Storing of Concrete Test Specimens for Use in Approval Testing of Sealers".

The qualifying test results shall be the average of three test specimens.

4.2 PERFORMANCE REQUIREMENTS

Test procedures for waterproofing and vapour transmission performance shall be according to BT001, "Alberta Test Procedure for Measuring the Vapour Transmission, Waterproofing and Hiding Power of Concrete Sealers".

Test procedures for alkaline resistance shall be according to BT002, "Alberta Test Procedure for Alkaline Resistance of Penetrating Sealers for Bridge Concrete".

4.2.1 Waterproofing Performance

The table below shows the minimum waterproofing performance requirements for each type of sealer.

SEALER TYPE	BEFORE ABRASION WATERPROOFING PERFORMANCE	AFTER ABRASION WATERPROOFING PERFORMANCE
Type 1a	82.6%	75.0%
Type 1b	82.6%	82.6%
Type 2a	82.6%	N/A
Type 2b	90.0%	N/A
Type 3	75.0%	N/A

4.2.2 Vapour Transmission Performance

The table below shows the minimum requirements for Vapour Transmission Performance for each type of sealer.

SEALER TYPE	MINIMUM VT
Type 1a	N/A
Type 1b	70%
Type 2a	35%
Type 2b	20%
Type 3	35%

4.2.3 **Alkaline Resistance Performance for Type 1 Sealers**

Alkaline resistance performance shall be performed on the same test cubes as used for the waterproofing performance test. After 21 days of exposure to potassium hydroxide waterproofing performance shall be within 3% of the actual measured after abrasion waterproofing performance.

4.2.4 **Hiding Power and Colour for Type 3 Sealers**

Type 3 Sealers must also meet the following:

a) Hiding Power - shall be measured according to the method 14.1 of Canadian General Standards Board CGSB 1-GP-71 and performed using the rate of coverage established at the time the sealer is applied to the test cubes in test procedure BT001 paragraph 4.4. If the product fails this hiding power test at this stage the product will be rejected.

b) Colour - shall be similar to colour identification Code 501-316 as shown in the Canadian General Standards Board 1-GP-12c, Section 5, Colour Samples.

5.0 PACKAGING

5.1 QUALITY AND SIZE

Containers shall be of adequate strength with an air tight lid. The size of the containers required will be specified on the order.

5.2 MARKING

The following information shall be marked on the outside of each container:

(a) Dangerous goods warning where applicable should be found on the label.

(b) Product name

(c) Manufacturer

(d) Batch number

(e) Volume of material

(f) Date material was manufactured.

At time of shipping the product must not have been manufactured for more than 30 days.

(g) Shelf Life

(h) If 2 component designate A or B and indicate ratio of component mixtures.

6.0 QUALITY CONTROL

6.1 APPROVED PRODUCT

Only products previously approved as meeting this specification will be considered for tenders calling for sealer products. The approved products will be shown on the approval list as to type, name, application rate, retest date, manufacturer and Alberta supplier.

The Supplier in submitting a tender is certifying that the product supplied is of the formulation used for the approval tests. Any subsequent change in the product will require a re-test for re-approval at the Supplier's expense.

The approval is valid for 3 years. If there has been no change in the formulation at that time the supplier may request a further 3 year approval. A Statutory Declaration will be required stating that the product meets the formulation as previously tested.

6.2 PRODUCT INFORMATION

The Supplier shall submit with his tender the current manufacturer's product data sheet and safety data sheet for each product being tendered.

6.3 REJECTS

The Department reserves the right to run laboratory tests and reject material that does not meet the requirements of the specifications.

The charges for these tests will be to the Department. If further testing is required the charges shall be to the Supplier.

7.0 TENDER AWARD

The tender award will be based on the individual product coverage rates established during the laboratory testing and supply of the volume of sealer required to provide the required protection to the tendered area of concrete surface. The area of concrete to be sealed will be stated on the tender. The amounts of each individual approved sealer needed to cover the tendered area will be stated on the tender.

Alberta Transportation and Utilities provides copies of the following documents to be used in conjunction with B388, Specification for the Supply of Concrete Sealers.

B390	Specification for Casting and Storing of Concrete Test Specimens for Use in Approval Testing of Sealers
BT001	Alberta Test Procedure for Measuring the Vapour Transmission, Waterproofing and Hiding Power of Concrete Sealers.
BT002	Alberta Test Procedure for Alkaline Resistance of Penetrating Sealers for Bridge Concrete, Concrete Sealer Test Report Form, Lab Data Acquisition Form.
	Concrete Sealer Test Report Form
	Lab Data Acquisition Form
	The following published procedure is available from The American Society for Testing and Materials.
ASTM D5095	Standard Test Method for Determination of Nonvolatile Content in Silanes, Siloxanes and Silane-Siloxane Blends Used in Masonry Water Repellent Treatments.

THE TRANSPORTATION RESEARCH BOARD is a unit of the National Research Council, which serves the National Academy of Sciences and the National Academy of Engineering. It evolved in 1974 from the Highway Research Board, which was established in 1920. The TRB incorporates all former HRB activities and also performs additional functions under a broader scope involving all modes of transportation and the interactions of transportation with society. The Board's purpose is to stimulate research concerning the nature and performance of transportation systems, to disseminate information that the research produces, and to encourage the application of appropriate research findings. The Board's program is carried out by more than 270 committees, task forces, and panels composed of more than 3,300 administrators, engineers, social scientists, attorneys, educators, and others concerned with transportation; they serve without compensation. The program is supported by state transportation and highway departments, the modal administrations of the U.S. Department of Transportation, the Association of American Railroads, the National Highway Traffic Safety Administration, and other organizations and individuals interested in the development of transportation.

The National Academy of Sciences is a private, nonprofit, self-perpetuating society of distinguished scholars engaged in scientific and engineering research, dedicated to the furtherance of science and technology and to their use for the general welfare. Upon the authority of the charter granted to it by the Congress in 1863, the Academy has a mandate that requires it to advise the federal government on scientific and technical matters. Dr. Bruce Alberts is president of the National Academy of Sciences.

The National Academy of Engineering was established in 1964, under the charter of the National Academy of Sciences, as a parallel organization of outstanding engineers. It is autonomous in its administration and in the selection of its members, sharing with the National Academy of Sciences the responsibility for advising the federal government. The National Academy of Engineering also sponsors engineering programs aimed at meeting national needs, encourages education and research, and recognizes the superior achievements of engineers. Dr. Robert M. White is president of the National Academy of Engineering.

The Institute of Medicine was established in 1970 by the National Academy of Sciences to secure the services of eminent members of appropriate professions in the examination of policy matters pertaining to the health of the public. The Institute acts under the responsibility given to the National Academy of Sciences by its congressional charter to be an adviser to the federal government and, upon its own initiative, to identify issues of medical care, research, and education. Dr. Kenneth I. Shine is president of the Institute of Medicine.

The National Research Council was organized by the National Academy of Sciences in 1916 to associate the broad community of science and technology with the Academy's purposes of furthering knowledge and advising the federal government. Functioning in accordance with general policies determined by the Academy, the Council has become the principal operating agency of both the National Academy of Sciences and the National Academy of Engineering in providing services to the government, the public, and the scientific and engineering communities. The Council is administered jointly by both Academies and the Institute of Medicine. Dr. Bruce Alberts and Dr. Robert M. White are chairman and vice chairman, respectively, of the National Research Council.

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Systematic, well-designed research provides the most effective approach to the solution of many problems facing highway administrators and engineers. Often, highway problems are of local interest and can best be studied by highway departments individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation develops increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

In recognition of these needs, the highway administrators of the American Association of State Highway and Transportation Officials initiated in 1962 an objective national highway research program employing modern scientific techniques. This program is supported on a continuing basis by funds from participating member states of the Association and it receives the full cooperation and support of the Federal Highway Administration, United States Department of Transportation.

The Transportation Research Board of the National Research Council was requested by the Association to administer the research program because of the Board's recognized objectivity and understanding of modern research practices. The Board is uniquely suited for this purpose as it maintains an extensive committee structure from which authorities on any highway transportation subject may be drawn; it possesses avenues of communication and cooperation with federal, state, and local governmental agencies, universities, and industry; its relationship to the National Research Council is an insurance of objectivity; it maintains a full-time research correlation staff of specialists in highway transportation matters to bring the findings of research directly to those who are in a position to use them.

The program is developed on the basis of research needs identified by chief administrators of the highway and transportation departments and by committees of AASHTO. Each year, specific areas of research needs to be included in the program are proposed to the National Research Council and the Board by the American Association of State Highway and Transportation Officials. Research projects to fulfill these needs are defined by the Board, and qualified research agencies are selected from those that have submitted proposals. Administration and surveillance of research contracts are the responsibilities of the National Research Council and the Transportation Research Board.

The needs for highway research are many, and the National Cooperative Highway Research Program can make significant contributions to the solution of highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement rather than to substitute for or duplicate other highway research programs.

NOTE: The Transportation Research Board, the National Research Council, the Federal Highway Administration, the American Association of State Highway and Transportation Officials, and the individual states participating in the National Cooperative Highway Research Program do not endorse products or manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to the object of this report.

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The members of the technical committee selected to monitor this project and to review this report were chosen for recognized scholarly competence and with due consideration for the balance of disciplines appropriate to the project. The opinions and conclusions expressed or implied are those of the research agency that performed the research, and, while they have been accepted as appropriate by the technical committee, they are not necessarily those of the Transportation Research Board, the National Research Council, the American Association of State Highway and Transportation Officials, or the Federal Highway Administration of the U.S. Department of Transportation.

Each report is reviewed and accepted for publication by the technical committee according to procedures established and monitored by the Transportation Research Board Executive Committee and the Governing Board of the National Research Council.

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