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Sealing System Selection for Jointed Concrete Pavements

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SEALING SYSTEM SELECTION FOR JOINTED CONCRETE PAVEMENTS

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

Concrete pavement joints are cracks intentionally formed in the pavement to accommodate expansion and contraction due to temperature changes. Today, 98 percent of the agencies building and maintaining concrete roadways, and 100 percent of the agencies building and maintaining concrete airport pavements in the United States require the sealing of these joints for new pavements. There are two major reasons for sealing rigid pavement joints. The first is to reduce the amount of water infiltrating the pavement structure, which results in slab erosion and loss of support. The second reason is to minimize the entry of incompressible materials into the joint reservoir, resulting in point loading when slabs expand under hot temperatures and subsequent joint spalling damage. Another reason for sealing rigid pavement joints is to reduce the potential for dowel bar corrosion by reducing entrance of de-icing chemicals. The proper sealing and maintenance of concrete pavement joints thus seems to be essential for the overall performance of the rigid concrete pavement. This work seeks to find out the factors that affect sealant life and performance and how to mitigate these to improve performance and reasonably extend sealant and thereby pavement life.

CHAPTER 1

INTRODUCTION

1.1 Statement of the Problem

Joints are created in concrete pavements so that premature cracks due to temperature or moisture changes can be minimized and locally controlled. Figure 1 presents a typical cross section of a concrete pavement joint. The performance of concrete pavements depends to a large extent on the satisfactory performance of these joints. The common types of pavement joints are described by their function. These include transverse, longitudinal, construction and expansion joints. Most jointed concrete pavement failures can be attributed to failures at the joint rather than to inadequate structural capacity, [Federal Highway Administration (FHWA) Technical Advisory No. T 5040.30 1990]. Distresses that result from joint failure include faulting, pumping, spalling, corner breaks, blowups, and mid-panel cracking. A joint sealant is a material introduced into the joint to minimize the infiltration of surface water as well as incompressible material into the joint system. Secondarily, sealants are also purported to reduce the potential for dowel bar corrosion by reducing entrance of de-icing chemicals, [Morian and Stoffels 1998]. The infiltration of water into a pavement's layers contributes to subgrade and subbase softening leading to pumping of subgrade or subbase fines under heavy traffic. This degradation can result in loss of structural support, pavement settlement and/or joint faulting. When incompressible material enters the joint reservoir, they obstruct pavement expansion in hot weather and create compressive pressure along the joint faces. This contributes to spalling and sometimes induces pavement migration and blow-ups.

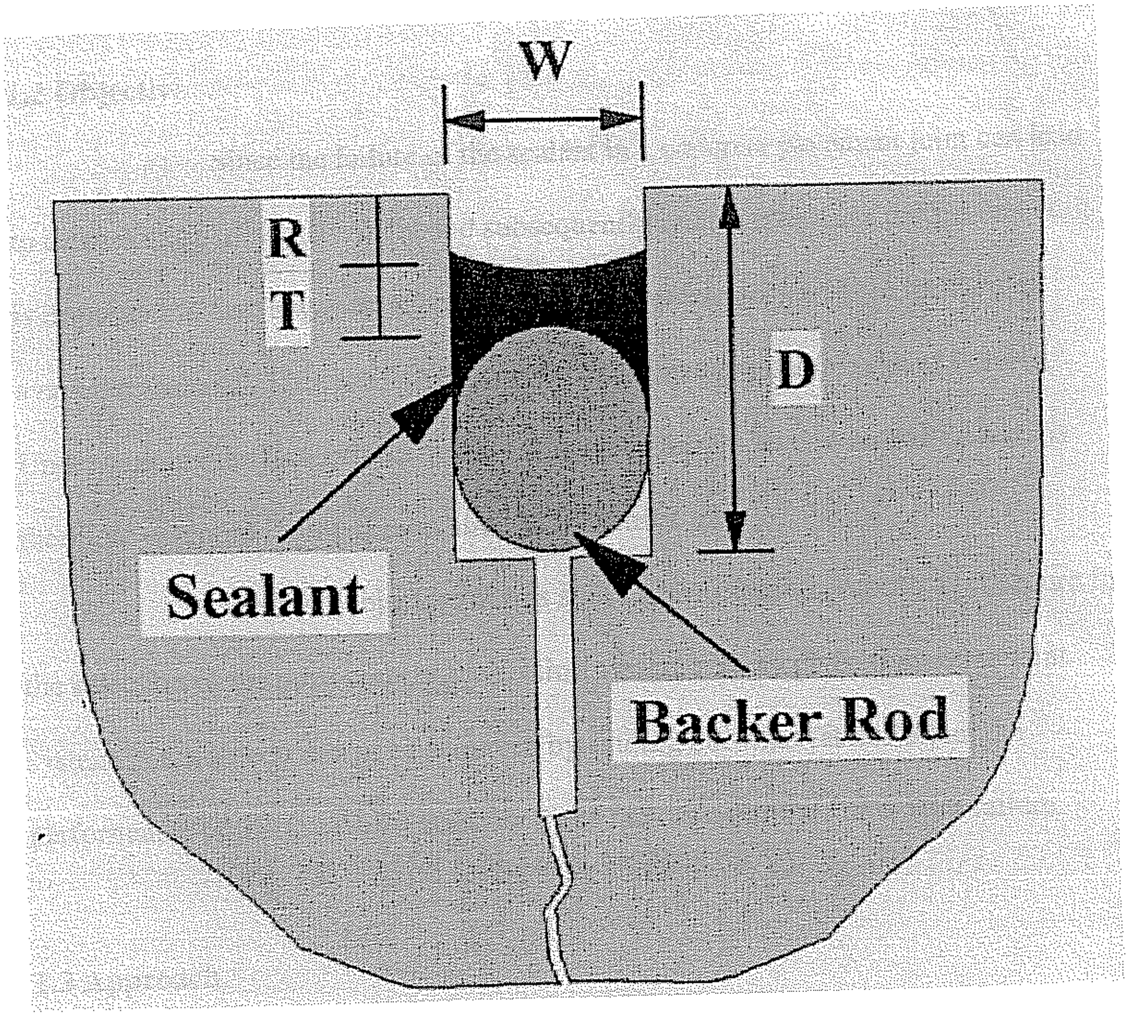


Figure 1: Typical Joint Cross Section [FHWA No. T5040.30 1990]

The main joint sealant failure types are adhesive, cohesive, intrusion, and extrusion. The failure of the sealant itself is not catastrophic. However this failure can lead to a great reduction of the service life of the surrounding pavement section. The depth, width, rheological properties and most importantly, workmanship quality, affect the performance of the joint sealants. The failure mechanisms of the joint systems need to be better understood in order to select a more compatible sealant for use in any joint system.

1.2 Objective

Since the failure of the sealant in a concrete pavement joint can lead to deterioration of the pavement and subsequently reduce the life of the pavement, it is important to find a way to select the most appropriate sealant from the host of available sealants. This would help prevent/minimize premature sealant failures. Understanding the factors, and in what way these factors lead to sealant failures is therefore essential for the preservation of pavement life.

The main objective of this study is therefore to propose a procedure for the selection of the most compatible sealing system for any given transverse joint system. This objective will be achieved by finding out what factors affect the performance of joint sealants, and how these factors contribute to sealant failure.

1.3 Approach

The objective of this study will be achieved through the following approach:

1. Conducting a comprehensive literature review of available work on concrete pavement joint sealants

2. Conducting case studies with the help of responses from questionnaire sent out to various state Departments of Transportation and data from SHRP-H-355 sites
3. Analyzing the results of these case studies and data available from the SHRP-H-355 studies
4. Concluding with the selection procedure of the most appropriate sealing system for any given joint system

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

As it is not practicable to construct and continuously maintain a completely watertight pavement, highway agencies have generally resorted to inserting sealants into the joints of concrete pavements to minimize the infiltration of water and incompressible materials. One major problem facing these agencies involved with the maintenance of these concrete pavements is the premature failure of the sealant materials with the attendant deterioration of the joint performance. This leads to the need for additional repair at extra cost to the agencies. Several factors affect the life and performance of these joint sealant materials in service as will be discussed in this chapter.

The different types of joints, characteristics of the different sealant materials available, the factors affecting their performance in service, and ways to evaluate and improve their performance have been researched into and documented in several publications over the years. The rest of this chapter will cover some of this material.

2.2 Types of Concrete Pavement Joints

The FHWA Technical Advisory Number T5040.30 [1990] defines and describes concrete pavement joints as presented in this section. The most common types of pavement joints are as defined by their functions:

1. Transverse joints
2. Longitudinal joints
3. Construction joints and
4. Expansion joints

2.2.1 Transverse Contraction Joints

Transverse contraction joints are saw formed or tooled grooves in a concrete slab that create a weakened vertical plane. They regulate the location of the cracking caused by dimensional changes in the slab. For this purpose, contraction joints should be deep enough to ensure that cracking occurs at the desired location rather than in a random pattern. These are the most common type of joints introduced in concrete pavements. Transverse joints control the cracking that results from the tensile and bending stresses in slabs due to cement hydration process, traffic loading, and the environment. Because these joints are so numerous, their performance significantly impacts on pavement performance. A distressed transverse joint typically exhibits faulting and/or spalling. Poor joint performance frequently leads to further distresses such as corner breaks, blowups, and mid-panel cracks. Such cracks may themselves begin to function as joints and develop similar distresses. The performance of transverse joints is related to three major factors, namely:

1. Joint spacing
2. Load transfer and
3. Joint shape and sealant properties

2.2.2 Longitudinal Joints

These are used to relieve warping distresses and are generally needed when slab widths exceed 4.57 meters (15 feet). Longitudinal joints should, whenever possible, coincide with pavement lane width to improve traffic operations. Load transfer at longitudinal joints is achieved through aggregate interlock. These joints should be tied with tie bars to prevent lane separation and/or faulting. Tie bars should be mechanically inserted and placed at mid-depth.

2.2.3 Construction Joints

There are two types of construction joints, transverse and longitudinal. A transverse construction joint should normally replace a planned contraction joint. They should however not be skewed as satisfactory concrete placement and consolidation would be difficult to obtain. These joints should be doweled and butted as opposed to keyed. This is because keyed construction joints tend to spall and are not recommended. It is recommended that transverse construction joints be sawed and sealed. The reservoir dimensions should be the same as those used for the transverse contraction joints.

The top of the slab above a keyway frequently fails in shear. For this reason it recommended that keyways not be used when the pavement thickness is less than 254 mm (10 inch). In such cases, tie bars should be designed to carry the load transfer. When pavement thickness is 254 mm (10 inch) or more however, a keyway may be used to provide the necessary load transfer. It is recommended that longitudinal construction joints be sawed and sealed. The reservoir dimensions should be the same as those used for the longitudinal joints.

2.2.4 Expansion Joints

Expansion joints have virtually been eliminated by good design and maintenance of contraction joints, except at fixed objects such as structures. When expansion joints are used, the pavement moves to close the unrestrained expansion joint over a period of a few years. As this happens, several of the contraction joints may open, effectively destroying their seals and aggregate interlock. The width of an expansion joint is typically 19.05 mm (0.75 inch) or more. Filler material is placed 19.05 mm (0.75 inch) to 25.4 mm (1 inch) below the slab surface to allow space for sealing material. Smooth dowels are the most widely used method of transferring load across expansion joints. Expansion joint dowels are specially fabricated with a cap in one end of each dowel. This creates a void in the slab to accommodate the dowel as the adjacent slab closes the expansion joint. Pressure relief joints are intended to serve the same purpose as expansion joints, except that they are installed after initial construction to relieve pressure against structures and to alleviate potential pavement blowups. Pressure relief joints are not recommended for routine installations. They may however be appropriate to relieve imminent structure damage or under conditions where excessive compression stresses exist.

2.2.6 Concrete Pavement Joint Movement

Joint movement in concrete pavements comprises of two components: shrinkage due to curing, and thermal expansion/contraction, where the thermal expansion and contraction includes the component of warping. With the initial shrinkage of the curing concrete, the joint will open up such that the elongation properties of the sealant become critical. The depth to width ratio of a sealant, commonly referred to as a shape factor, typically ranges from 1 to 1.5. The depth of the joint sealant has a major effect on the stresses and strains applied to the sealant due to the joint movement. This leads to high stresses along the sealant/joint interface, leading to cohesion and/or adhesion failure of the sealant.

When the concrete pavement cools down in the evening, the joint widens as a function of the slab length. This increased joint width due to temperature differential can be calculated using the following equation [Gurjar et al. 1998]:

$$\delta L = CL(\alpha \delta T + e)$$

where δL = change in joint width in mm; C = subgrade constant (0.65 for stabilized and 0.8 for granular); L = length of spacing in mm; α = thermal expansion coefficient of concrete (1.1×10^{-5} mm/mm/°C); δT = change in temperature in °C; and $e = 0$ if maintenance work is on an existing pavement.

2.3 Characteristics of Sealants for Jointed Concrete Pavements

The sealant used in the joints must be capable of withstanding repeated extension and compression as the slab temperatures change. The quality level of joint sealant materials should increase as the expected joint movement increases due to longer slab length, higher temperature change, higher concrete thermal coefficient, and lower friction between slab and subbase. The ideal characteristics of sealants as presented by Gurjar et al. [1998] are:

1. Staying resilient at all temperatures
2. Not softening during hot weather
3. Not hardening brittle during cold weather

Two most critical characteristics of a jointed concrete pavement sealing material are cohesion and adhesion. Commonly used joint sealant materials exhibit differing degrees of adhesion and cohesion.

2.4 General Sealant Classifications

Concrete pavement joint sealants may be classified into the following three categories:

1. Hot-poured sealants: asphalt mastics filled with latex, butyl, or reclaimed rubbers. For this category of sealants, elastic properties are lost when they are overheated.
2. Cold-poured sealants: polyurethanes, polysulfides, silicone, and modified epoxies. This category of sealants has low modulus, reduced temperature sensitivity, good adhesive and cohesive strength, but high material cost.
3. Preformed Sealants: premolded strips of styrene, urethane, polychloroprene, neoprene, or other synthetic rubbers. These sealants are precompressed and inserted by a special tool.

2.5 Criteria for Evaluating Sealant Products

Sealant products are commonly evaluated by the following six criteria according to Biel et al. [1998]:

1. Elasticity - This is the sealants ability to return to its original size when stretched or compressed.
2. Modulus: This is the change in internal stresses in a sealant while being stretched and compressed over a range of temperatures. Low modulus is desirable and is particularly important in cold weather climates.
3. Adhesion – This is the ability of the sealant to adhere to the concrete. Both initial and long-term adhesion is equally important.
4. Cohesion – This is the ability of the sealant to resist tearing from tensile stress.
5. Compatibility – This is measured by the relative reaction of a sealant to materials it comes into contact with.
6. Weatherability - This is the ability of the sealant to resist deterioration when exposed to elements such as ultraviolet sun rays and ozone.

2.6 Factors Influencing Sealant Performance

The performance of the sealants can be influenced by the following factors presented by Biel et al [1998]:

1. Movement of joint
2. Sealant reservoir shape
3. Bonding between sealant and sidewall
4. Properties of the sealant

5. Voids under the joint

6. Poor workmanship/inspection

7. Environmental factors

2.7 Sealant Products

2.7.1 Hot-Poured Rubberized Asphalt Sealants

According to Morian and Stoffels [1998], hot-pour sealants are generally the least expensive of the sealant materials. Some years ago hot-poured rubberized asphalt sealants predominated all sealant types used for rigid concrete pavement joint sealing. This material requires several factors to ensure that the joints are properly sealed and will remain so for some time. Many pavement agencies have used ASTM D3405 rubberized asphalt material for the past 15 to 20 years. Prior to that, ASTM D1190 material was often used. Due to the fact that inferior performance has been identified with the use of this material, its use has been widely discontinued. ASTM D3406 material has more recently been considered for use. This material seems to provide better performance at a somewhat increased cost. However, none of these hot-poured rubberized materials seem to perform as well, or cost as much as silicone or compression seals materials. For the sealant to perform properly, a sealant reservoir for hot-pour materials must have a recommended shape factor of 1:1. This shape factor provides the minimum relationship between the reservoir width and depth to achieve the required adhesion performance characteristics of the material. The use of a backer rod to ensure the proper shape factor is critical to the performance of hot-poured sealing materials. The backer rod ensures that sealant material bonds only to the sides and not to the bottom of the reservoir.

2.7.2 Silicone Sealant Materials

A range of differing materials falling within the description of this category are classified as silicone joint sealants. These types of sealants often require the use of a primer or bonding agent. Silicone sealants can be broadly classified as self-leveling and non self- leveling. The non self-leveling silicone materials require a hand-tooled finish. Classifying on the overall scale of commonly used sealant materials by highway agencies, the silicone sealants give an intermediate performance at an intermediate cost.

When using silicone sealant materials, a width to depth ratio of 2:1 is generally required. The use of a backer rod to ensure that proper dimensions are obtained is recommended. Some silicone materials have been known to fail to bond with certain limestone aggregates. Instances of this have been reported in Virginia, Michigan, and Iowa [Morian et al. 1998].

2.7.3 Compression Seal Materials

Compression seal materials are designed to always remain in a compressed state ranging between 20 to 60 percent. In contrast to the design of hot-poured rubberized asphalt and silicone materials, which are applied in the liquid state and must both stretch and adhere to the pavement once cured, compression seals are applied in the solid state. Their design and installation must be such that they always remain in a compressed state at both maximum and minimum joint-opening width. If the condition of joint crack occurrence is overlooked, the compression seal will fail to perform when the joint cracking does not initially take place at the joint. In such a situation the sealant material will be required to expand beyond the limits of its elastic properties. As a result, the compression seal material will fail to perform as expected.

Compression seals also typically require the use of a primer or bonding agent for installation. The lubricating effect of a primer is necessary for installation because the seal is larger than the sealant reservoir into which it is installed. Whether the primer contributes to cohesion of the seal to the pavement is a moot issue because the seal will not remain in place if movement exceeds the required compressed state. This is usually 70 percent [Morian et al. 1998].

One problem identified with compression seal material focused on the chemical composition of the rubber material produced. This is a quality control of production problem. Another problem relates to the development of compression set in the seal. This problem relates to the fact that the acceptance test, ASTM D2628, requires 83 to 88 percent rebound, but only for a single cycle. This testing does not preclude compression set of the seal material. Additional problems have been associated with poor construction quality control, particularly overcutting the depth of the sealant reservoir [Morian et al. 1998].

2.8 Filled Joints

Some past practices often resulted in the construction of rigid pavement joint that was never effectively sealed. Such are described as filled joints. The filled joint primarily serves to exclude the majority of large incompressible materials from entering the joint reservoir and causing joint spalling. These joints do not effectively prevent the penetration of water from the base and subgrade layers below. This results in joint erosion.

Joints have most frequently been filled with asphalt-based materials including ASTM D1190 and D3405 materials. Joint-filling materials have frequently not remained in place for many years, and this practice has been largely discontinued. Some agencies have however despaired of properly sealing joints and have therefore been satisfied with attempts to fill them. These efforts were however frequently not maintained and joints were effectively unsealed [Morian et al. 1998].

Data and observations from SHRP SPS-4 test sections indicate that both spalling and the presence of incompressible materials in the joint reservoir are greater when joints are left unsealed [Morian et al. 1998].

2.9 Sealed Versus Unsealed Joints

Hall and Crovetti [1998] carried out research to compare the performance as measured by distress of jointed plain concrete pavements (JPCP) designed and constructed with unsealed joints, with that of JPCP with sealed joints. This work was based on data available from the Long Term pavement Performance (LTPP) studies. The analysis considered the performance of pavement sections included in the Specific Pavement Studies (SPS) and the General Pavement Studies (GPS) pavements (SPS-4). The five suitable SPS-4 sites selected were: Mesa, Arizona; Campo, Colorado;

Tremonton, Utah; Salt Lake City, Utah; and Heber City, Utah. Table 2.1 gives the global matrix of joint sealant-versus-design groups represented in the test sections, and Table 2.2 gives the number of test sections in each joint sealant-versus-design group.

Table 2.1 Global Matrix of Joint Sealant-Versus-Design Groups represented in the Test Sections at the Five SPS-4 Supplemental Study Sites. [Hall and Crovetti1998]

		Conventional Saw				Soff-cut Saw
Unsealed		3 mm	6 mm	9mm	9 mm bevel	3 mm
Asphalt	Crafco RS 221	A				B
	Crafco SS 444					
	Koch 9005			C		
	Koch 9012					
Silicone	Crafco 902					
	Crafco 903-SL					
	Dow 888					
	Dow 888-SL	D	E	F	G	H
	Dow 890-SL					
	Mobay 960					
	Mobay 960-SL					
Neoprene	DS Brown E-437H					
	DS Brown V-687					
	DS Brown V-812					
	Kold Seal Neo Loop		I	J		
	Esco PV 687					
	Watson Bowman 687					
	Watson Bowman 812					
Polysulfide	Koch 9050-SL			K		
Proprietary	Roshek			L		

The analysis conducted in this study did not indicate that unsealed joints are any more likely to develop joint spalling than sealed joints. At two of the five sites studied, no joint spalling was observed in any test section. At two other sites, minor spalling was reported in some unsealed-joint and sealed-joint test sections. At one site, the only spalling observed was reported in a sealed-joint test section. Campo, Colorado, the youngest site, showed no significant differences in faulting among any of the joint sealant groups. It is significant to note that this is the only one of the five sites which has doweled joints.

Table 2.2 Number of Test Sections in Each Joint Sealant-Versus-Design Group, at Each SPS-4 Supplemental Study Site. [Hall and Crovetti 1998]

Group	Mesa, AZ	Campo, CO	Tremonton, UT	Salt Lake City, UT	Heber City, UT
A	2	2	2	2	2
B			1	2	2
C	4		4	4	4
D	2	4	2	2	2
E	2	4			
F	10	5	6	4	4
G		2			
H			1	2	2
I		1	2	2	2
J	4	1	2	2	2
K				2	2
L			1		
Number of test sections	24	19	21	22	22
Number of nonempty groups	6	7	9	9	9 supplemental study site.

At the other four sites, faulting tends to be highest in the 3-mm unsealed group (A), and the 9-mm silicone-sealed group (F). At three of the five sites the rate of increase in International Roughness Index (IRI) was highest in the 3-mm unsealed group (A), but at one site it was lowest in this group and at the fifth site, it was no different than in the other groups. Group A and F, and in some cases group B (3-mm Soff-Cut unsealed), have had the highest IRIs among the treatment groups. Worth noting however is the fact that in every case, the order of treatment groups by IRI is no different after five, seven or nine years in service than it was in the first year after construction. This underscores the importance of analyzing data on initial IRI values and rates of IRI increase rather than just IRI magnitudes in later years to detect significant differences in roughness development by treatment type. These sites are located in the dry western part of the United States.

In general, the narrow unsealed test sections did exhibit more faulting and higher rates of IRI increase than most other treatment groups. The same is however true of the 9-mm silicone-sealed group F. It is unknown why this sealed-joint design would differ from the others in terms of faulting and IRI. The significance of this however is that it would be an inaccurate overgeneralization to conclude that the unsealed-joint treatment resulted in more faulting and roughness than the sealed-joint treatments. The narrow unsealed test sections (groups A and B), formed by using riding saws and Soff-Cut saws respectively, had actually tended to exhibit better deflection load transfer and other joint deflection responses than the sealed-joint test sections. At some sites, one or both of these unsealed-jointed groups exhibited higher total deflections for both loaded and unloaded sides of the joint than the sealed-joint groups. Total joint deflection was the only joint deflection parameter that could potentially be correlated to the higher faulting and IRI in the unsealed-jointed test sections. It was however not concluded on the basis of these analysis results that such a correlation exists.

One reason for doubting that correlation exists is that it would not explain the higher faulting in the group F test sections which did not necessarily have higher total joint deflections. In three of the five sites, the sealed-joint test sections were not necessarily well sealed. They had moderate to severe joint-seal damage. How well the sealed-joint test sections were really sealed is a factor that should be considered in future analysis of the long-term performance of the pavements at these test sites. Also since all these sites are located in the dry western region of the United States, these findings cannot be extrapolated to other regions of the country that receive more precipitation.

According to Shober [1997], Wisconsin State Department of Transportation (WisDOT) in 1974 to begin a study of pavement performance as influenced by sealed and unsealed contraction joints at various spacing. More than 50 test sections (typically 300m long) were accordingly constructed from 1974 to1988 in:

1. Doweled and undowelled pavements
2. Pavements with subgrades varying from sand to silt to silty clay with varying traffic loading
3. Two- and four-lane pavements in both rural and urban situations,
4. Pavements on dense and open-graded bases, and
5. Plain and reinforced pavements

Results on performance of these test sections in 1996 led to the conclusions that joint sealing appeared to have no significant effect on pavement distress, pavement ride quality, bridge encroachment and materials integrity. WisDOT research indicated that the best overall PCC pavement performance is achieved with narrow, unsealed joints. The next best performance comes with sealed joints. The worst performance results from partially sealed or filled joints. Shober [1998] noted that every sealed joint will decay into a partially sealed joint unless a strict resealing regimen is followed. Even with such a strict regimen, the pavement performance will not equal an unsealed system. A cost analysis indicated that Wisconsin saves $6 million dollars a year by not using sealed joints.

Burke Jr. and Bugler [2002] examined the case for and against the use of unsealed jointed concrete pavements in a follow up to Shober [1997]. The study evaluated the WisDOT research and Western European observations about the long term-term performance of unsealed jointed pavements. The conclusions of this study are presented below.

Valid conclusions about the performance of concrete test-pavements can only be made if performance evaluations recognize that gradual, progressive and unseen changes are taking place within the structure. These changes can and generally do have a progressively adverse effect on the long-term performance of these pavements. The use of unsealed pavement joints has been largely ineffective in providing long-term cost-effective pavement performance. Enhanced long-term performance requires not just the use of joint seals though, but choosing high quality sealant material type and size for the chosen pavement joint and panel characteristics. Also, effective installation and inspection procedures and periodic sealant repair and replacement practices must be carried out.

Valid generalized conclusions about the efficacy of certain highway pavement characteristics cannot be achieved based on extrapolations of short term *(≤ 10 years)* pavement performance observations. This is valid where such conclusions are concerned about the long-term (≥ *30 years*) performance of highway pavements exposed to heavy traffic, fine incompressible roadway debris, moving water, and a broad range of environmental variables. This is especially true when those extrapolations from a single local geographical area are presumed to be applicable to a wide range of geographical, geological and environmental applications. For jointed pavements exposed to heavy traffic and broad environmental variables, well-maintained pavements with doweled and sealed joints, as well as stabilized well-drained bases provide the most functional, durable and cost-effective pavement applications.

Based on early findings on the evaluation of 5 years of performance of the long-term pavement performance (LTPP) specific pavement studies (SPS) relating to rigid pavement maintenance activities SPS-4, Morian and Stoffels [1998] indicated that joint-seal sections are performing better than unsealed sections. It was too early to see the benefits of the maintenance treatments on the pavement life though. The observations made with respect to sealing or not sealing concrete pavement joints are presented below.

Regarding the exclusion of water, sealing of pavement joints may not be cost-effective in pavement locations with free-drained, coarse-grained subgrade material. In locations where pavement joints are thermally locked a large portion of the year, detection of performance differences between sealed and unsealed pavement joints may be difficult to discern. Thus it would be reasonable to assume that not sealing joints is a cost-effective practice.

Pavement expansion pressures can be shown to be quite high, and pavement migration has resulted in damage to structures in a number of states. Pavement migration and the resulting blowups are not addressed by the unsealed joint practices.

The single 3-mm saw cut is not adequate to appropriately deal with slab contraction movement in temperate climates which experience temperature extremes (-18°C – 38°C).

Problems experienced by many joint-seal designs result from inadequate construction quality control. Further problems with joint-seal designs result when temperatures during the early cure cycle of rigid pavements do not vary over a sufficiently wide range; thus all joints do not initially crack the full depth of the slab. This condition results in extreme opening of those joints that do crack, causing any such theoretically designed joint seals to fail. Based on the above observations the following recommendations were made:

1. More detailed evaluation of joint movement specific to climate and pavement design parameters is appropriate in conducting local pavement design.
2. Greater consideration of joint-seal installation quality should be incorporated into quality control/quality assurance programs.
3. Evaluation of pavement performance resulting from various joint-sealing practices in various design and environmental conditions should be long term to provide useful conclusions.
4. Where thermal-locked joints in dry climates and/or coarse-grained subgrade exist, the practice of using a single, 3 mm saw cut joint may be cost effective when evaluated in the context of long-term pavement performance.
5. In wet and wet-freeze climates with fine-graded subgrade materials, it is unlikely that the unsealed joint concept will result in cost-effective pavement performance. This is particularly true where antiskid materials are used during frozen

conditions as these materials will result in incompressibles in the pavement joints causing spalling damage or pavement blowups.

The available literature thus builds a better case for joint sealing as opposed to not sealing jointed rigid pavement joints.

2.10 Bonding

The integrity of any joint sealant in a concrete pavement depends heavily on the adhesion between the interface of the sealant and the walls of the concrete reservoir, for this purpose termed the substrate. The strength of this adhesion is dependent on many variables and their interactions with each other. The adhesion strength should be strong enough to withstand all static and dynamic stresses applied to the sealant-substrate interface. These stresses could be due to seasonal temperature changes, daily traffic, or distresses like faulting in the pavement. Gurjar et al. [1998] carried out an experimental program to study the factors that affect the bonding of joint sealants to concrete. The factors investigated included the surface preparation technique, aggregate type in concrete substrate, temperature and humidity during curing, and sealant type. A series of analysis of variance tests were conducted to analyze the data.

Four different sealant types representing the three commonly used categories (silicone, asphalt and polyurethane) were investigated. Aggregate type was tested at two levels, siliceous river gravel and crushed limestone. The three levels of surface preparation employed were water-blast, sandblast, and sandblast plus primer. Curing temperatures and humidity were investigated at 40°C and 10°C, 95 percent and 50 percent respectively.

The experimental study demonstrated that not all sealants are affected by the same factors, and that performance depended on material type and classification. While the silicone-based sealants were found to be highly influenced by surface preparation type and curing temperature, the aggregate type used in the concrete substrate significantly influenced the asphalt-based materials. This suggests that the additional cost of priming may be justified because of gain in bond strength for silicone sealants. Higher substrate temperature seemed to be beneficial to the asphalt materials. This investigation however, only serves as a base for more detailed investigation of factors affecting bond strength in concrete pavement sealants.

Rogers et al. [1999] suggest that before choosing a sealant the ASTM C794 adhesion-in-peel test be performed on the sealant to assess concrete/sealant adhesion. This will allow the most suitable sealant for the expected service conditions to be selected.

2.11 Deformation and Environmental Factors

Rogers et al. [1999] present a test protocol that correlates sealant viscoelastic properties with the sealant resistance to deflection. Since a sealant must be flexible enough to withstand excessive conditions like large temperature fluctuations, severe pavement deflection due to heavy truck traffic, and prolonged moisture exposure, the authors propose that the selection of a sealant should be based on a complete evaluation consisting of three test procedures:

1. The ASTM C794 adhesion-in-peel test to assess concrete/sealant adhesion

2. Dynamic mechanical analysis (DMA) to evaluate sealant flexibility by determining the glass transition temperature (T_g)
3. A shear fatigue test developed by the writers to analyze sealant performance when subjected to severe pavement deflection in combination with various environmental conditions like temperature and moisture

The DMA will be performed only for sealants that pass step 1. After the DMA, only sealants that cure at an acceptable rate possess a T_g below the expected in-service temperature range, and exhibit the least degradation due to water/chemical exposure will be considered best candidates for the shear test. Again only sealants that show no visible signs of failure will undergo DMA to determine the effect of mechanical fatigue on the sealant molecular bonding. The authors conclude that the test procedure does correlate sealant performance with viscoelastic properties and hence, allows the most suitable sealant for the expected service conditions to be selected.

Al Qadi et al. [1999] attribute the inability to predict sealant performance to the fact that there is no laboratory evaluation method that accurately simulates field traffic and environmental loading conditions. The authors thus developed a laboratory testing method that allows the evaluation of joint sealants under cyclic shear and static horizontal deflections. Shear deflection simulates vehicular loading, and horizontal deflection simulates expansion and contraction of concrete slabs due to temperature variation.

Concrete specimens were prepared at a typical water-to-cement ratio of 0.45. Two aggregate types (granite and limestone) were used in the concrete mixes to evaluate the effect of aggregate type on sealant performance. Two commercially available sealants (a low-modulus one-part cold-applied silicone and a one-part cold-applied polyurethane) were investigated in the study. The polyurethane sealant was used with a primer. Sealant performance was evaluated for different joint widths and joint expansion. Specimens were loaded cyclically to failure. A 20 percent cohesive or adhesive debonding was considered a failure. A limited number of specimens were exposed to freezing and thawing cycles to assess their effect on sealant performance. Statistical models were developed to predict the number of loading cycles to failure for each sealant.

Each test specimen consisted of two concrete cubes (50.8mm) and a sealant sandwiched between them. The sealant shape factor, i.e. depth-to-width ratio, was chosen to be 1. This study resulted in the development of laboratory testing technique to evaluate rigid pavement joint sealants under field-simulated conditions. From evaluating the two different sealant types (silicone and polyurethane) using the developed fixture, it was found that sealant performance is greatly affected by joint width, joint extension, and aggregate type used in the concrete. An insignificant effect, however, was noted due to temperature changes and freezing and thawing cycles. Polyurethane with concrete containing granite was affected in the first 30 cycles of freezing and thawing. The study recommends the use of a primer when silicone is used with concrete containing limestone because of incompatibility between silicone and limestone. In addition, joint width should be kept at a reasonable size to optimize the fatigue life and stress resistance capability.

Margesson et al. [1996] also carried out research to compare the relative influences of sustained deformation and environmental exposure on the mechanical properties of a sealant. One- component polyurethane sealant specimens were cast between sections of aluminum substrate, cured at standard conditions for 21 days and then subjected to deformations ranging from 50 percent compression to 75 percent extension. Specimens were divided into three groups: one group remained at standard conditions, (control), another group was mounted in a xenon arc weathering device and the remaining group was placed in a forced air oven. After 500 hours of exposure specimens were returned to standard conditions and then tested to failure. The sealant characteristics monitored were recovery from deformation, ultimate elongation, tensile strength, strain energy to break and the nature of failure. Both elongation and strain energy were discriminating indicators of changes in the mechanical properties of the sealant. The conclusions drawn from this study were:

1. Prolonged compression caused a marked reduction in the ultimate elongation capacity of the selected polyurethane sealant, while prolonged extension resulted in higher elongation capacity compared to undeformed specimens.
2. Elongation capacity and strain energy to break were discriminating indicators of changes in ultimate mechanical properties of the selected sealant-substrate system. Tensile strength was of limited use in this regard. Elongation capacity is recommended as the preferred indicator because it is easier to determine, and it relates most directly to the desired performance characteristics of a sealant.
3. Exposed sealant specimens exhibited lower recoveries from both compression and extension than their control counterparts. This is attributed to either polymer chain reorientation or changes to the cross linking structure within the sealant.

4. The failure mechanism changed from adhesive to cohesive in specimens that received both exposure and sustained extension. This is attributed to a decrease in their cohesive strength due to either polymer chain reorientation or chemical bond disruption.
5. Five hundred hours of exposure to heat aging and xenon arc accelerated weathering is not sufficient to cause significant chemical degradation in the sealant.
6. Heat aged and weathered specimens behaved similarly after 500 hours of exposure. This suggests that the effect of elevated temperature alone was observed, and that the effects of UV and water were less significant.

2.12 Joint Seal Design and Installation Methods

Morian and Stoffels [1998] notes as a critical issue in the design of joint seal, the quality of construction applied in constructing the joint reservoir and installing the sealant material. A sample for one site monitored as part of the SHRP H-106 experiment recorded construction dimensions for joint reservoir width; joint reservoir depth; depth to top of backer rod, and depth to top of sealant. All the sites were specially constructed experimental test sections which receive close scrutiny, and therefore generally exceed the average level of construction quality found on normal production projects. In spite of it measurements for all categories fell outside the tolerance range sets. The authors have observed excessive variations in joint reservoir depths on several field projects from joint to joint, with overcutting of reservoir depth being the most common flaw. Another difficulty in the installation of rigid pavement joint seals is ensuring that the reservoir walls are dry and clean at the time of installation. Construction installation is therefore a major factor in sealant performance.

Another construction-related factor vital to joint-seal performance is the fact that depending on ambient temperature during concrete pavement placement, all pavement joints induced by saw-cutting frequently do not crack under initial thermal loading stresses. The detrimental result of this phenomenon is that the joints that do not crack are not contracting according to the theoretical joint movement calculated for the designed joint spacing. They contract as though the joint spacing were much greater. A joint seal designed on the basis of 6 meter joint spacing cannot perform when only every third joint has cracked and resulting movement contracts for an 18 meter slab. The cohesive and adhesive properties of the sealant material cannot possibly perform under these conditions. This naturally occurring phenomenon can be addressed by carefully monitoring the conditions under which paving and slab curing take place. It has generally been associated with large temperature swings in daily maximum and minimum temperatures on the order of 25°C to 28 °C. Less swings in the order of 10 °C to 16 °C do not produce these results. Another important factor in the contraction of rigid pavement slabs is the friction exerted on the slab by the pavement base as it responds to thermal stresses. Changing base material friction characteristics without revising joint design practices to accommodate for the change is another reason joint seals fail. For example, as agencies moved from dense-graded aggregates base courses to lean concrete or open-graded stabilized bases, friction interaction characteristics changed. Until these differing friction characteristics have been adequately characterized, joint spacing based on aggregate bases is by random chance.

FHWA [1990] identifies some of the characteristics that contribute to satisfactory joint performance as adequate load transfer, proper concrete consolidation, quality construction materials, and good construction and maintenance procedures. Regardless of the joint sealant material used, periodic resealing will be required to ensure satisfactory joint performance throughout the life of the pavement. The performance of transverse contraction joints is related to three major factors:

a) Joint spacing

b) Load transfer across the joint

c) Joint shape and sealant properties

The advisory emphasized the need for attention to detail in pavement joint construction and outlined the proper procedures to follow to achieve good quality and durable pavement joints. It specifically outlined measures to be taken in concrete placing especially around the joints. Guidelines for reservoir design according to the advisory are as follows:

1. For silicone sealants, a minimum shape factor of 1:2 is recommended. The maximum shape factor should not exceed 1:1. For best results, the minimum width of the sealant should be 9.5 mm (3/8 inch). The surface of the sealant should be recessed 6.35 mm (1/4 inch) to 9.5 mm (3/8 inch) below the pavement surface to prevent abrasion caused by traffic. The use of a backer rod is necessary to provide the proper shape factor and to prevent the sealant from bonding to the bottom of the joint reservoir. This backer rod should be a closed-cell polyurethane foam rod having a diameter approximately 25 percent greater than the width of the joint to ensure a tight fit.

2. When using preformed compression seals, the joints should be designed so that the seal will be in 20 to 50 percent compression at all times. The surface of the seal should be recessed 3.175 mm (1/8 inch) to 9.5 mm (3/8 inch) to protect it from traffic.

The advisory recommended that all joints be sawed and gave the guidelines for this procedure as follows:

1. Sawing should be a two-phase operation. The initial sawing is intended to cause the pavement to crack at the intended joint. It should be made to the required depth with a 3.175 mm (1/8 inch) wide blade. The second sawing provides the necessary shape factor for the sealant material. This second sawcut can be made any time prior to the sealant installation. However, the later the sealant reservoir is made, the better the condition of the joint face. Both sawcuts should be periodically checked to ensure proper depth, as saw blades tend to wear as well as ride up when hard aggregate is encountered. Periodic measurement of blade diameter is an excellent method to monitor random blade, particularly when using gang saws.
2. Time of initial sawing, both in the transverse and longitudinal directions, is critical in preventing uncontrolled shrinkage cracking. It is very important that sawing begin as soon as the concrete is strong enough to both support the sawing equipment and to prevent raveling during the sawing operation. All joints should be sawed within 12 hours of concrete placement. The sawing of concrete constructed on stabilized base must be done earlier. This is particularly critical

during hot weather. Once sawing begins, it should be a continuous operation and should only be stopped if raveling begins to occur.

3. For transverse contraction joints, an initial sawcut of D/3 (D = thickness of concrete slab) is recommended, particularly for pavements with a thickness greater than 10 inches. In no case should the sawcut depth be less than D/4. Transverse contraction joints should be initially sawed in succession. Skip sawing is not recommended as this results in a wide range of crack widths that form beneath the sawed joints. These varied crack widths affect the shape factors and may cause excessive sealant stresses in those joints initially sawed. The dimensions of the final sawing should be dependent upon the sealant type and the anticipated longitudinal slab movement.
4. For longitudinal joints, a minimum initial sawcut depth of D/3 is recommended to ensure cracking at the joint. The maximum sawcut depth should be such that the tie bars are not damaged. A final sawing that provides a 3/8-inch wide by 1-inch deep sealant reservoir should be sufficient.
5. When a lengthy period is anticipated between the initial sawing of the joint and the final sawing and sealing, consideration should be given to filling the joint with temporary filler. This filler material should keep incompressibles out of the joint and reduce potential spalling.
6. The use of plastic inserts is not recommended. Although a few states have had success with these inserts, most states no longer allow their use. Improper placement of plastic insets has been identified as a cause of random longitudinal cracking. It is also very difficult to seal the joint formed by these inserts.

American Concrete Pavement Association [1995] states that over time all pavement joint sealants suffer accumulated distress. Sealants can lose external bond with joint reservoir sidewalls or lose internal bond and split open. They can also lose their flexibility through natural aging and long-term exposure to oxygen, ozone, and sunlight. To extend pavement life, joint sealants must be replaced periodically. Successful resealing consists of five steps: 1. removing old sealant, 2. shaping the reservoir, 3. cleaning the reservoir 4. installing the backer rod and 5. installing the sealant.

The best ways to carry out the 5-step procedure to obtain optimum results are outlined. For removal of old sealant, it described manual removal, sawing, plowing and cutting. For step 2, the paper stated that shaping is unnecessary if the sealant was removed by hand and existing reservoir provides adequate dimensions. Also sawing out the old sealant provides an adequate reservoir and should not require this step. It is also stated that minor spalling along the joint face would not inhibit performance of the sealant; however, some patching may be needed for larger spalls. Reservoir faces require thorough cleaning to ensure good sealant adhesion and long-term performance. The association's paper prohibited the use of chemical solvents for washing the reservoir in step 3. The paper suggested that immediately after sawing, the slurry must be washed away in one direction to avoid contamination of surrounding areas. After the joint has dried sufficiently, the joint should be sandblasted to remove any remaining residue. The sandblast nozzle must be held at an angle close to the surface to clean the top inch of the joint face. This also provides texture to improve sealant adhesion. After this the joint and pavement surface must be air blasted to remove sand, dirt and dust just before pumping the sealant. At the backer rod installation stage, it was recommended that the rod be compatible with the liquid sealant and have a diameter 25% greater than the reservoir width. Also the backer rod must be inserted at the proper depth and the insertion wheel must be rolled over it twice. The final stage, installation of the sealant, requires that manufactures' instructions be strictly adhered to.

Research carried out by ERES Consultants for the Federal Highway Administration and published as Publication No. FHWA-RD-99-137 and [Evans Lynn D. and Romine A. R. 1993] evaluated the performance of selected sealant materials. Other objectives were to determine the effect of selected sealant configurations and installation methods, and to identify sealant material properties and tests that correlate well with field performance. Test sites were located on moderate- to high-volume, four-lane highway or interstate pavements in four climatic regions. Two sites were located in the wet freeze region to compare the effects of short and long jointed pavements on sealant performance. One thousand six hundred joints were resealed at 5 test sites using 12 sealant materials and 4 methods if installation. The four methods of installation were: 1. joint faces resawed and sealant recessed 2. joint faces resawed and sealant overbanded 3. joint faces plowed and sealant overbanded and 4. joint faces resawed and sealant flush-filled. The sealants used were:

1. One ASTM D 3405 asphalt sealant namely Koch 9005
2. Three low-modulus ASTM D3405 asphalt sealants, namely, Crafco Roadsaver7 (RS) 231, Meadows Sof-Seal 7, and Koch 9030
3. Two ASTM D 3405 rubberized asphalt sealants, namely, Meadows Hi-Spec7 and Crafco RS 221

4. Two-self leveling silicone sealants, namely, Dow Corning7 888-SL and Mobay Baysilone 960-SL
5. One non-self leveling silicone sealant: Dow Corning7 888

Single installations were also made at the request of the participating states for the following sealants: 1. Koch 9050 – Self-leveling, one part polysulfides; 2. Mobay Baysilone 960 – Self-leveling silicone sealant and 3. Crafco RS 903 - Self-leveling silicone sealant.

Ten evaluations were performed and the parameters used were partial-depth adhesion loss; full-depth adhesion failure; partial-depth spall failure; full depth spall failure; overband wear; stone intrusion; partial-depth cohesive failure, and full-depth cohesive failure.

For 82 months, field performance data on the different sealant and installation methods were collected at each site. The key findings over the study period pertinent to installation procedure and workmanship were as follows:

1. Overbanding of hot-applied sealants using a squeegee notched 3 mm by 35 mm showed better results than recessed and flush-filled joint seals. This is thus recommended, especially for low-volume roadways.
2. Sandblasting each joint face was used at all sites with good results, especially with silicone sealants. Single sandblast passes should be avoided. Dual passes are recommended. Jigs or other methods of reducing operator fatigue and ensuring that the sand blast nozzle is properly positioned are recommended.

3. Nozzles or tooling devices are recommended to ensure that silicone sealant is installed from the bottom of the joint, and that it is not exposed to traffic.
4. For sealing projects that are designed to be overlayed in less than 6 years, good-performing hot-applied sealants, such as Crafco RS 231 and Koch 9005, are recommended.

2.6 Performance of Different Sealant Materials

Biel and Lee [1997] state that field studies of laboratory-approved sealants have indicated that many sealants that performed successfully in the laboratory often failed prematurely in the field. Adhesion failure is the most common cause of failure and it could start as early as 1.5 years after installation. The objectives of their research project were to:

a. Determine the service lives of three different types of sealants, i.e. polyvinyl chloride- (PVC) coal tar, rubberized asphalt, and silicone
b. Measure their impacts on the performance of concrete pavements in Utah
c. Recommend construction and maintenance strategies that will improve the performance of the sealants and pavements

The conditions of nine pavement sections were examined to determine the effects of sealant condition on pavement distresses, namely, joint spalling along the surface of the joint, faulting o f the joint and conical spalling at the bottom of the joint. The criteria for evaluating sealant products generally are:

1. Elasticity

2. Modulus

3. Adhesion

4. Cohesion

5. Compatibility

6. Weatherability

Nine sites were selected for detailed inspection and evaluation under traffic control, with 20 joints inspected at each site. Joint spalling and faulting were determined through visual inspection. Filling the voids in the core with putty and measuring the volume of putty used determined conical spalling at the bottom of the joints. Two 150 mm cones were taken at each site for visual inspection of the pavement condition below surface. This resulted in the discovery of severe conical spalling at the bottom of the joints where joint sealants had failed. Silt and evidence of infiltration were present in all cases, but incompressibles were present only in the pavements with failed sealants. Performance curves for the three sealants were developed with respect to their ages. The data collected from test sections with silicone showed good performance over a 10 year span, while those with the PVC-coal tar and rubberized asphalt material were at the end of their service life. The sites for the PVC-coal tar and rubberized asphalt material were far beyond their design lives. Several of the rubberized asphalt sealant samples were observed to be partially oxidized; however the material was still pliable. Much of the PVC-coal tar material was completely oxidized and hardened without any resilience or pliability. Based on the limited set of the data used in this study, the service lives of the PVC-coal tar and rubberized asphalt are believed to be less than ten years. Due to the wide range of ages, it was not possible to choose the best type of sealant with a significant level of confidence. More data on the performances of PVC-coal tar and rubberized asphalt are needed.

Recommendations for joint configurations and maintenance programs based on the use of silicone or rubberized asphalt materials for sealing are:

1. Original joint configuration for the sealant be 6 mm wide and 6 mm deep (shape factor of 1)
2. Resealing of the joints must be done after 10 years and joints must be re-cut to a width of 9 mm and a depth of 9 mm

Table 2.3 provides sealant information for the nine sites, and Table 2.4 gives a summary of the evaluation data.

Table 2.3 Test Section Locations and Sealant Information [Biel et al. 1997]

Site Number	Joint Width (mm)	Sealant	Year Installed
1	9	PVC-coal tar	1980
2	9	Silicone	1985
3	9	Silicone (PVC-coal tar)	1984
4	9	Silicone	1991
5	3	Rubberized asphalt	1975
6	3	PVC-coal tar	1976
7	3	Rubberized asphalt	1966
8	3	Rubberized asphalt	1970
9	9	Silicone	1988

In 1989, the US Army Engineer Research and Development Center and Crafco Incorporated initiated a research effort to develop improved materials and processes for resealing joints in Portland cement concrete (PCC) pavements. One objective of this research was to develop specification limits for improved field performance of hot-applied, jet-fuel-resistant (JFR) and non-jet-fuel-resistant sealants.

Table 2.4 Summary of Sealant Evaluation Data for Nine Test Sections [Biel et al. 1997]

Material	Age (year)	Survival Rate (%)	Failure type	Joint Width (mm)	Spalling Core 1	Spalling Core 2	Incompressibles
PVC-coal tar	13	37.45	cohesion	11.2	44.4 cc	34.9 cc	None
Silicone	8	85.25	adhesion	10.9	24.1 cc	21.8 cc	None
Silicone	11	79.75	adhesion	10.9	8.0 cc	3.6 cc	Minimal 6-mm stones
Silicone	2	98.25	adhesion	12.2	0.8 cc	1.7 cc	Some 3-mm stones
Rubberized asphalt	18	15.00	Cohesion/loss	7.4	Core in pieces	157.2 cc	Some 6-mm stones
Rubberized asphalt	17	0.00	cohesion	6.9	141.5 cc	30.3 cc	Minimal
Rubberized asphalt	27	5.00	loss	7.4	52.7 cc	178.0 cc	Many 3-mm stones
Rubberized asphalt	23	7.5	Loss	6.1	53.7 cc	240.3 cc	Many 3-mm stones
Silicone	5	86.75	Adhesion/loss	9.7	18.4 cc	21.5 cc	None

The second was to obtain field data to determine the field performance of different sealants and installation configuration. Lynch et al. [2002] write that the research effort was divided into two phases: laboratory and a field phase. The laboratory phase focused on identifying ideal properties that hot-applied non-JFR sealants should possess; evaluating commercially available sealants to determine if they exhibit those properties; and developing improved hot-applied materials that would exhibit as many of those properties as feasible. The field phase was initiated in June 1991 at Fairchild Air Force Base near Spokane, WA. The study area was divided into two – Area 1 and Area 2. Area 1 had twenty four test sections numbered 1 through 24 while Area 2 had 10 test sections numbered 1 through 10. The focus of this effort was to determine the field performance of field molded sealants (including improved materials) versus commercially available sealants, as well as whether field performance could be improved by changing the sealant installation geometry. Thirteen different field-molded sealants were installed and their field performance monitored at different times over a ten year period, namely at 6, 12, 22, 58, and 117 months. The evaluations generally indicated that two of the hot-applied asphalt-based sealants, four of the silicone-based sealants, and one of the coal tar-based sealants had life expectancies of greater than 10 years. The improved JFR and non-JFR sealants exhibited better field performance than the standard hot-applied sealants included in the evaluation. Details of evaluation of the different periods are as follows:

During the six-month evaluation survey, ambient temperature ranged from –4°C to 2°C. The overall performance of the sealants was very good after six months. The most common defect noted in the non-JFR and JFR hot-applied materials was bubbling. Many of the hot-applied sealants had experienced surface bubbling during installation and the bubbling appeared to increase in size and quantity during the initial six months. This may have been due to softening of the sealant that allowed moisture vapor to escape through the sealant.

The twelve-month evaluation ambient temperature ranged from 20°C to 24°C. The primary defect noted as in the six-month survey was bubbling in the non-JFR and JFR hot-applied sealants. There was significant amount of bubbling in the hot-applied sealants, but it did not appear to adversely impact on the performance of the sealant. Overall adhesion failure had increased slightly, but they still averaged less than one percent. Many of the adhesion failures appeared to initiate in areas where old joint sealant had been removed during the joint preparation. Minor partial depth adhesion loss was noted in many of the hot-applied sealants. The hot-applied sealants were beginning to peel away from the joint face to a depth of approximately 1.6 mm to 3.2 mm. These areas were not classified as adhesion failures because the failures were not full depth. All sealants were performing satisfactorily at the 12 month evaluation. However, the cold-applied, single- and two-component sealants appeared to be performing better than the hot-applied sealants.

The twenty-two month evaluation had temperatures ranging from 10°C to 13°C. Some differences in sealants began to be noticed at this evaluation. The overall condition of the non-JFR sealants in Area 1 appeared to be similar to the 12-month evaluation. There was still significant amount of bubbling, but it did not appear to have worsened from the previous evaluation. The hot-applied sealants continued to exhibit partial depth adhesion loss. The Mobay 960SL material also exhibited partial depth adhesive loss. The other silicone sealants did not exhibit any adhesive, cohesive, or spalling defects. In Area 2, the Crafco Superseal 1614A sealant exhibited significant amounts of adhesive and cohesive failures. The sealant appeared to be hardening from the top and bottom surfaces. The other JFR sealants were performing satisfactorily with limited or no adhesive or cohesive defects.

The 58-month evaluation temperatures ranged from 4°C to 7°C. Significant differences began to become apparent at this evaluation. The two sealants Crafco Superseal 1614A and Koch Product 9005 had adhesion loss greater than 50 percent. On government projects 25 to 50 percent adhesion or cohesion loss would be considered failure, i.e., the sealant should be replaced. The silicone materials and the “improved” JFR and non-JFR materials appeared to be performing the best at 58 months, but in general, the overall sealants performance remained satisfactory.

Ambient temperatures for the 86-month evaluation ranged between 21°C to 27°C. There seemed to be a decrease in the amount of adhesive failure in the hot-applied sealants except for the Crafco Superseal 1614A and Koch Product 9050SL which exhibited an increase. Ambient temperatures were higher than during the previous evaluations. The joints were narrower, and the sealants were softer, creating a “healing effect”. This may have been the probable reason for the apparent improvement or decrease in adhesion loss of the hot-applied sealants. Table 2.5 provide sealant type and installation information while Table and 2.6 provides the 117-month evaluations.

Table 2.5 Sealants and Installation Configurations [Lynch et al. 2002]

Area	Sealant	Configuration	Type of sealant
1	Crafco Roadsaver 222	3.2 to 6.4 mm recess	Hot-applied rubberized asphalt sealant manufactured to meet the requirements of FS SS-S-1401C
1	Crafco Roadsaver 222	Flush with the pavement surface and overband	
1	Crafco Roadsaver 222	3.2 to 6.4 mm recess and all joints were primedd	
1	Crafco Improved Non-JFR	3.2 to 6.4 mm recess	Hot-applied rubberized asphalt sealant manufactured to meet the requirements of FS SS-S-1401C and improved low temperature bond and adhesion properties
1	Crafco Improved Non-JFR	Flush with the pavement surface and overband	
1	Crafco Improved Non-JFR	3.2 to 6.4 mm recess and all joints were primedd	
1	Crafco Roadsaver Silicone SL	Sealant installed according to manufacturer's guidance	Cold applied single-component self-leveling silicone sealants to meet the requirements of ASTM D5893 Type SL
1	Mobay Silicone 960	Sealant installed according to manufacturer's guidance	Cold applied single-component non-sag silicone sealant (no longer available)
1	Mobay Silicone 960 Self-Leveling	Sealant installed according to manufacturer's guidance	Cold applied single-component self-leveling silicone (no longer available)
1	Koch Product 9005	Sealant installed according to manufacturer's guidance, selected joints were primed	Hot-applied rubberized asphalt sealant manufactured to meet the requirements of FS SS-S-1401C
1	Dow Corning 902 RCS	Sealant installed according to manufacturer's guidance	Two-component self-leveling cold applied silicone sealant
1	Dow Corning 890 SL	Sealant installed according to manufacturer's guidance	Cold applied single-component self-leveling low-modulus silicone sealant which meets requirements of ASTM D5893 Type SL
2	Crafco Superseal 1614A	Sealant installed according to manufacturer's guidance	Hot-applied polymer modified tar based material manufactured to meet requirements of FS SS-S-1614A
2	Crafco Improved JFR	Sealant installed according to manufacturer's guidance	Hot-applied polymer modified tar based material that has lower modulus than FS SS-S-1614A and improved low temperature bond properties and improved long-term aging characteristics
2	Koch Product 9050 SL	Sealant installed according to manufacturer's guidance	Single-component cold-applied polysulfide-based material (no longer available)
2	Koch Product 9020	Sealant installed according to manufacturer's guidance	Two-component cold-applied polysulfide-based material manufactured to meet requirements of FS SS-S-200E (no longer available)
2	Koch Product 9012	Sealant installed according to manufacturer's guidance, selected joints were primed	Hot-applied polymer modified tar based material manufactured to meet requirements of FS SS-S-1614A and ASTM D3569 (no longer available)

Table 2.6 Sealant Elongation at 117 Months [Lynch et al. 2002]

Sealant	Percent Elongation	Failure Type[a]
Crafco Roadsaver 222	300%	Cohesive break
Crafco Improved Non-JFR	600%	Cohesive break
Crafco Silicone SL	300%	Cohesive break
Koch Product 9005	0	Material 'gooey'. Could not conduct test
Mobay 960 SL	50%	Cohesive break
Dow 902 RCS	600%	Cohesive break
Dow 890 SL	600%	Adhesive loss
Mobay 960	50%	Cohesive break
Crafco Superseal 1614A	0	No material remaining in joints
Crafco Improved JFR	250%	Cohesive break
Koch Product 9050 SL	150%	Cohesive break
Koch Product 9012	75%	Cohesive break
Koch Product 9020	200%	Cohesive break

Notes:

a - Failure type refers to how the sealant failed at the end of the elongation test. Cohesive break means that the sealant broke at the elongation listed. Adhesion loss means that the sealant began pulling away from the joint face at the elongation listed.

Eacker and Bennett [2002] present a report on five sealant materials used in Michigan. A test section of pourable sealants was placed on reconstructed I-94 between Watervliet and Hartford in 1994. Five sealants, Dow 888 and 890SL, Sikaflex 15LM and 1CSL, and Crafco Roadsaver SL, were each used to seal 60 contraction joints. Preformed neoprene, Michigan's standard sealant, was used on the remainder of the job. The sealants were visually evaluated and rated twice a year for three and a half years. Joint sealing occurred after 20 days so the concrete had 20 days of cure time. This exceeds the seven day industry recommendation. Sikaflex 15LM, Dow 890SL, and Dow 888 sections were completed on sunny days with temperatures ranging from 15°C to 27°C during operations. Joint reservoirs were sawed 14mm ± 1.5 mm wide and 63 mm deep. Each sealant was used in 60 consecutive joints. The remainder of the new pavement was sealed with 32 mm preformed neoprene. Longitudinal joints were sealed with hot-pour rubber asphalt.
The transverse sealant was placed in the longitudinal joint for 300 mm in each direction from the transverse joint. The joints were sandblasted and then cleaned with compressed air immediately prior to sealing. Evaluation was by visual inspection of the sealant condition in the outside or driving lane. Inspections occurred approximately every six months.

A rating system of 1 to 5 developed by Pennsylvania Department of Transportation (Table 2.7) was used in three categories: sealing (adhesion to concrete), weathering, and debris intrusion. A rating of 5 was the best and meant the sealant was in the same condition as when it was placed. A rating of 1 meant that more than 50 percent of the sealant had failed. The number rating given depended on the amount of failure as measured along the length of the joint. Each joint was rated in the three categories and then an average was found for each material. The same person did the rating each time so that subjectivity between raters would be avoided. A section of joints sealed with neoprene was also visually inspected, but not rated. Tables 2.8, 2.9 and 2.10 contain the average ratings after each evaluation for sealing, weathering, and debris intrusion respectively. Weathering was not a problem for any of the materials. The lower ratings for weathering in the later evaluations were due to several joints that had very little to no sealant left. Any debris in the joint was due to failures of the sealant so that debris intrusion was a function of sealing. Sikaflex 1CSL was the only of the pourable sealants that performed close to satisfactorily. It had the best sealing rating after 44 months. One-third of the joints showed some signs of adhesive loss. All but one of these had less than 5 percent (18 cm) failure as measured along the length of the joint, which is a rating of 4. This resulted in a fairly good final rating of 4.6. The next best performer was Dow 890SL with a rating of 4.4. Seventy-five percent of the Dow 890SL joints had some adhesion loss. All of the failures were less than 5 percent of the joint length. Following closely behind was Sikaflex 15LM. Just over half of the Sikaflex 15LM joints experienced adhesive failure. The majority of these were rated as 4, but five joints had more than 50 percent failure. The concern is whether those small adhesive losses will increase with repeated joint openings and closings over the next several winters. Typically, adhesive failures tend to progress like a zipper after a winter of joint movement. Sealing ratings continued to drop, suggesting that the failures that were already present were increasing.

Table 2.7 Pennsylvania DOT Joint Seal Rating Levels [Eacker et al. 2002]

Joint Sealing Rating Levels		
Rating	**Degree (non conforming)**	**Description**
Sealing /Adhesion to concrete		
5	None	Seal is intact and in the same condition as constructed
4	Slight	Seal has experienced adhesion, cohesion, and or raveling defects in less than percent of the joint length
3	Moderate	Seal has experienced adhesion, cohesion, and or raveling defects in less than 25 percent but more than 5 percent of the joint length
2	Severe	Seal has experienced adhesion, cohesion, and or raveling defects in less than 50 percent but more than 25 percent of the joint length
1	Deteriorated	Seal has experienced adhesion, cohesion, and or raveling defects in more than 50 percent of the joint length
Weathering		
5	None	Seal is intact and in the same condition as constructed
4	Slight	Seal surface aged or oxidized
3	Moderate	Seal surface has weather checking
2	Severe	Seal surface has alligator cracking
1	Deteriorated	Seal surface has eroded
Debris Intrusion		
5	None	Seal is intact and in the same condition as constructed
4	Slight	Seal is intact and in the same condition as constructed with debris accumulated, but no intrusion
3	Moderate	Seal has accumulated debris with scattered intrusion
2	Severe	Seal has accumulated debris with much intrusion
1	Deteriorated	Seal is broken and eroded by excessive intrusion of debris

The last rating however went up for all three. This may possibly be due to the fact that the 44 month evaluation was done on a day with higher ambient temperatures. The joints would therefore be closed more and therefore smaller adhesive failures would be harder to see. Crafco Roadsaver SL declined rapidly within the first year. All but one of the sixty joints sealed with Crafco Roadsaver SL had failures. Roughly two-thirds of the failures were cohesive, making this the only sealant to see that type of failure. Cohesive failures were common when the sealant width to depth ratio is too large or too small. Typically the sealant should be placed so that the depth is about half the width. Several depths were checked for the depth of sealant by pulling up the failed area. In all but one case, the sealant depth was proper. This suggests that the material is weak when extended. Another possible explanation is that it takes longer to fully cure. This increases the chances of it being extended during this weaker state when the joint opens due to temperature decreases. Dow 888 ended up the worst performer. It also commenced on a fast deterioration rate that continued throughout the evaluations. Only four of the sixty joints had no signs of failures. Twenty-seven had more than 25 percent failure along the length of the joint with 16 having more than 50 percent failure. This was typical of the failures seen in Michigan when silicones fail. They fail quickly.

During each evaluation the sixty neoprene sealed joints were looked at. After 44 months the neoprene was in the same condition as when it was installed. The amount of movement these sealants experienced was also monitored. Ten consecutive joints in each section were pinned and measured for the first year to ascertain whether they were moving and the relative amount. Measurements were taken at the same time as the visual evaluation of the sealants. The coldest temperature during measurements was -4 °C, and the warmest was 24 °C. Going from cold to warmer temperatures, 87 percent of the pinned joints did close.

Table 2.8 Average Ratings for the Sealing Category [Eacker et al. 2002]

Sealing Ratings								
Evaluation Date	**Feb. 95**	**Aug. 95**	**Feb. 96**	**Oct. 96**	**May 97**	**Oct. 97**	**May 98**	**Apr 99**
Dow 888	5.0	4.7	4.2	4.1	3.1	2.8	2.6	2.3
Dow 890SL	4.9	4.8	4.6	4.6	4.4	4.3	4.4	4.0
Sikalex 15LM	4.9	4.8	4.5	4.4	4.2	4.1	4.2	3.6
Sikaflex 1CSL	4.9	4.8	4.6	4.6	4.5	4.5	4.6	4.2
Crafco Roadsaver SL	4.7	4.4	3.8	3.6	3.6	3.5	3.4	3.1

Table 2.9 Weathering Ratings for the Weathering Category. [Eacker et al. 2002]

Weathering Ratings								
Evaluation Date	**Feb. 95**	**Aug. 95**	**Feb. 96**	**Oct. 96**	**May 97**	**Oct. 97**	**May 98**	**Apr 99**
Dow 888	5.0	5.0	5.0	5.0	4.3	4.0	3.6	3.2
Dow 890SL	5.0	5.0	5.0	5.0	5.0	5.0	4.1	4.1
Sikalex 15LM	5.0	5.0	5.0	5.0	5.0	5.0	4.6	4.9
Sikaflex 1CSL	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
Crafco Roadsaver SL	5.0	4.9	5.0	5.0	4.7	4.6	4.5	4.9

Table 2.10 Average Ratings for the Debris Category [Eacker et al. 2002]

Debris Ratings								
Evaluation Date	**Feb. 95**	**Aug. 95**	**Feb. 96**	**Oct. 96**	**May 97**	**Oct. 97**	**May 98**	**Apr 99**
Dow 888	5.0	4.9	4.6	4.5	3.4	3.2	2.8	2.3
Dow 890SL	5.0	5.0	4.8	4.9	4.9	4.9	4.7	4.2
Sikalex 15LM	5.0	4.9	4.9	4.9	4.9	4.9	4.5	4.7
Sikaflex 1CSL	5.0	5.0	5.0	5.0	4.9	4.9	4.9	4.7
Crafco Roadsaver SL	4.9	4.8	4.3	4.1	4.1	4.0	4.0	3.7

Average and maximum movement for the February to August time period are given for each sealant material in Table 2.11.

Table 2.11 Average and Maximum Joint Movements for Each Sealant Section [Eacker et al. 2002]

Joint Movement		
Sealant	**Average Movement (mm)**	**Maximum Movement (mm)**
Dow 888	0.91	4.11
Dow 890 SL	0.91	1.70
Sikaflex 15LM	1.01	2.26
Sikaflex 1CSL	1.22	2.06
Crafco Roadsaver SL	1.24	2.16
Preformed Neoprene	1.32	1.91

FHWA-RD-99-146 [1999] is an update of the Strategic Highway Research Program (SHRP) manual of practice (SHRP-H-349) on concrete pavement repair. The Federal Highway Administration Long-Term Pavement Performance Program (LTPP) conducted five years of additional research on concrete pavement repair after the conclusion of SHRP. The manual presents updated guidelines and recommendations to assist highway maintenance agencies and other related organizations in planning, constructing, and monitoring the performance of concrete pavement joint resealing projects. Tables 2.12, 2.13 and 2.14 give typical recommended shape factors, typical joint design dimensions and joint preparation/installation procedures respectively. Table 2.15 provides a summary of sealant materials. Installation methods mentioned in the manual are:

1. Recessing the sealant below the pavement surface

2. Keeping the sealant surface level with the pavement surface

3. Overbanding sealant onto the pavement surface

Table 2.12 Typical Recommended Shape Factors [FHWA 146 1999]

Sealant Material Type	**Typical Shape Factor (Width : Depth)**
Rubberized Asphalt	1:1
Silicone	2:1
PVC Coal Tar	1:2
Polysulfide and Polyurethane	1:1

Table 2.13 Typical Joint Design Dimensions [FHWA 146 1999]

Maximum Joint Spacing (mm)	**Minimum Joint Width (mm)** [a]	
	Non-freeze Region [b]	**Freeze Region** [c]
≤ 4.6	6	10
4.7 to 7.6	6 to 10	10 to 13
7.7 to 12.2	10 to 13	13 to 19
12.3 to 18.3	13 to 19	19 to 29

a - Installation temperature is 27°C, base is stabilized, percent $E_{max} \leq 20\%$.

b - Minimum non-freeze region temperature is -7 °C.

b - Lowest freeze region mean temperature is -26 °C.

According to the manual, overbanded seals tend to oxidize at a lower rate than recessed asphalt-based sealants because of the massaging action of traffic tires. As a result, adhesion failures may occur more quickly in recessed sealants. A 7-year study of joint seals in the United States indicates that overbanded ASTM D 3405 seals have statistically outperformed recessed seals even when installed in transverse joints on heavily trafficked roadways. In longitudinal lane-shoulder joints, overbanding may provide better performance than recessed seals. In reduced traffic areas such as low-volume roads or lane-shoulder joints therefore, overbanded sealants may be the most effective choice. There are, however, two drawbacks of overbanding on PCC pavements. First, overbanded sealant material is typically worn away by traffic within 1 to 3 years. After it is worn, traffic tires tend to pull the sealant from the edge, leading to adhesion failure. Second, the scraping action of ice blades on highways in cold regions tends to pull up overbanded seals from the pavement. Silicone sealants should never be overbanded or flush with the pavement surface. Manufacturers recommend a minimum of 7 to 10 mm recess below the pavement surface for all silicone sealants to avoid premature adhesion failure.

Table 2.14 Joint Preparation/Installation Procedures [FHWA 146 1999]

Option	Plow	Saw	Water Wash	Initial Airblast	Sand Blast	Final Airblast	Backer Rod	Recessed Sealant
1		•	•	•	•	•	•	•
2		•		•	•	•	•	•
3	•	•		•	•	•	•	•
4	•				•	•	•	•

Table 2.15 Summary of Sealant Materials [FHWA 146 1999]

Sealant Material	Applicable Specifications	Design Extension % [a]
PVC Coal Tar	ASTM D 34	10 to 20%
Rubberized Asphalt	ASTM D 1190 AASHTO M 173 ASTM D 3405 ASTM M 301	15 to 30%
Low Modulus Rubberized Asphalt	Modified ASTM D 3405	30 to 50%
Polysulfide (1 & 2 Part)	Fed SS-S-200E	10 to 20%
Polyurethane	Fed SS-S-200E	10 to 20%
Silicone (non-sag)	ASTM D 5893	30 to 50%
Silicone (self-leveling)	ASTM D 5893	30 to 50%

a - Consult manufactures for specific design extensions

CHAPTER 3

CASE STUDIES

3.1 Introduction

Information regarding Portland Cement Concrete Pavement joint seal practices was solicited from all the fifty State Departments of Transportation through the use of questionnaire. Responses were received from 22 states including Delaware. Out of the responses received, ten (excluding Delaware) were from states located within the same climatic zone as Delaware. Information pertinent to this study could be derived from only ten out of the eleven received. The responses are presented in section 3.3 of this chapter.

3.2 Experimental Design/Questionnaire

Since climatic factors affect the performance of available joint sealants, the states were grouped into four climatic zones:

1. The wet-freeze zone
2. The wet-nonfreeze zone
3. The dry freeze zone
4. The dry nonfreeze zone

The zoning adopted in this study follows the regional divisions adopted by the Strategic Highway Research Program (SHRP). As Delaware falls within the wet-freeze zone, information from states within this zone is given more emphasis and detailed analysis.

The questionnaire was designed to obtain information regarding:

1. The type of sealants used by the different states.
2. How long these sealants have been used.
3. Traffic conditions on the roads.
4. The cost effectiveness of each sealant with respect to performance.
5. Any other pertinent information about sealants that the Departments may have.

The intent was to design a questionnaire that was simple enough to be filled without wasting the recipients' time, but which would provide enough information to be used in conjunction with available literature to provide a meaningful qualitative analysis. A sample of the questionnaire is provided in the Appendix.

3.3 Presentation of Responses

Results received from the states which fall into the defined climatic zones are tabulated below. The response from the State of Alaska is treated separately due to the uniqueness of its climate. The responses from Wisconsin and Ohio are also given in-depth treatment due to their anomalous nature.

WET-FREEZE ZONE

State	No. of Years of Sealant Use	Types of Sealants Used	Truck Traffic on Sealed Jointed Pavements	Cost/Unit Length of Sealants Used ($/ft)	Observations and Comments About Sealant Use
Delaware	20	All sealants conforming to AASHTO M 301 or AASHTO M 282	High and Medium	Varies from $1.00/ft to $6.00/ft	1. The use of sealants does contribute to an increase in pavement life, justifying its usage. 2. For the sealed joints to be truly beneficial, a preventive program of regular inspection and maintenance of the joints must be adhered to. 3. If the joints are left to deteriorate, the pavement condition declines rapidly.
New York	30+	- Hot-poured ASTMD3405 - Silicone - Neoprene	High and Medium	Unavailable	1. The use of sealant does contribute to an in increase in pavement life if installed properly. 2. The performance of the sealants justifies their usage. 3. NY State has used less neoprene since the early 1970s. 4. NY State has used Silicone extensively almost exclusively until recently. 5. NY State began using ASTM 3405in PCC joints in 2000, experimenting with single stage saw cuts for both longitudinal and transverse joints. 6. NY State uses ASTM 3405 as joint filler. 7. The experimental sites are still being monitored.

WET-FREEZE ZONE

State	No. of Years of Sealant Use	Types of Sealants Used	Truck Traffic on Sealed Jointed Pavements	Cost/Unit Length of Sealants Used ($/ft)	Observations and Comments About Sealant Use
Iowa	35	Cold Pour Asphalt Hot Pour Asphalt Silicone Neoprene	Medium	Cold Pour - $.05 Hot Pour - $.05 Silicone - $0.30 Neoprene – $0.40 (Rates for sealant material only)	1. The best performing sealant for Iowa DOT is hot pour. 2. The joints are early entry sawed and then filled with hot pour sealant. No backer rod is installed. 3. Neoprene seals can perform well if properly installed, but installation requirements for success are very hard to meet. 4. Silicone sealants do not perform much better than hot pour although silicone is 8 to 10 times more expensive including installation.
Kentucky	Sealing has always been part of all original construction	Hot Pour Asphalt Silicone Neoprene	Medium and High	Incidental item to cost of pavement.	1. Hot pour sealant preferred to other forms. 2. Silicone sealant is next preferred.

WET-FREEZE ZONE

State	No. of Years of Sealant Use	Types of Sealants Used	Truck Traffic on Sealed Jointed Pavements	Cost/Unit Length of Sealants Used ($/ft)	Observations and Comments About Sealant Use
Ohio	20+	Preformed Neoprene	Low, High, and Medium	Not available	1. The sealant has not contributed to pavement life extension. 2. Research has not yet provided any data that justifies the use of joint seals. 3. The DOT is currently revising standards and specifications to eliminate the use of sealants in concrete pavements.
Wisconsin	All forms of sealing has been terminated since 1997	N/A	N/A	N/A	1. Sealants do not contribute to pavement life extension. 2. Research indicates that unsealed jointed concrete pavements perform better than sealed ones. 3. The DOT has hence since 1997, discontinued sealing of concrete pavement joints.
Vermont	N/A	N/A	N/A	N/A	The state of Vermont has only very old concrete pavement joints which have long since been overlaid with asphalt concrete.
Indiana	20	Varies	Low, High, and Medium	Not Available	1. It is unknown whether sealants contribute to pavement life extension. 2. Cost effectiveness is unknown. 3. Studies currently underway.

WET-FREEZE ZONE

State	No. of Years of Sealant Use	Types of Sealants Used	Truck Traffic on Sealed Jointed Pavements	Cost/Unit Length of Sealants Used	Observations and Comments About Sealant Use
Connecticut	20	-Dow Corning 902 RCS -Dow Corning 888 NS -Hot Pour AASHTO M173	High	$36/oz $14/oz $.35/lb	1. The cost and performance of the sealants justify their use. 2. Dow Corning 902 RCS can handle up to 3" of movement. 3. Dow Corning 888 NS is used for vehicular surfaces. 4. Hot pour 1190 is used where there is limited thermal expansion.
Virginia	20	Preformed Neoprene Silicone Rubberized Hot Pour Hot Pour Asphalt	High and Medium	$ 2.00/ft $1.40ft $1.10/ft $0.75/ ft	1. The cost and performance of Silicone, Rubberized Hot Pour and Hot Asphalt justify their use. 2. The cost and performance of Preformed Neoprene does not justify its use. 3. Plain Hot Pour Asphalt is only used in longitudinal joints. 4. VDOT no longer uses Preformed Neoprene in pavement joints. 5. Silicone sealant is the most common sealant used by VDOT. 6. Rubberized Hot Pour is used for the maintenance of existing transverse joints.

DRY-FREEZE ZONE

State	No. of Years of Sealant Use	Types of Sealants Used	Truck Traffic on Sealed Jointed Pavements	Cost/Unit Length of Sealants Used ($/ft)	Observations and Comments About Sealant Use
Colorado	15	Dow 888-SL (Silicone)	Low, High and Medium	Incidental item to cost of pavement, but estimated to be approximately $0.40/ft	1. Self-leveling silicone sealants do not seem to work well in hot climates due to application problems. 2. Numerous air bubbles push through the sealant before it sets, creating voids. 3. DOT has asked contractors to switch to a different product. Contractors chose a non self-leveling product which seems to work better. 4. A backer rod is essential in the installation of the silicone sealant. It should be a closed cell backer rod and should be laid at the proper depth in the joint conforming to desired sealant depth. 5. The shape factor must also be maintained at 1:1 to perform best. 6. The narrower the joint, the better the sealant works. 7. Narrow joints also have the added advantage of reduced sealant cost. 8. It is of paramount importance to have the joints thoroughly cleaned before installation of sealant.

DRY-FREEZE ZONE

State	No. of Years of Sealant Use	Types of Sealants Used	Truck Traffic on Sealed Jointed Pavements	Cost/Unit Length of Sealants Used ($/ft)	Observations and Comments About Sealant Use
Colorado (continued)					9. The joint should be washed out while saw cutting to get rid of as much residue as possible. 10. The joint should then be sand blasted to further clean, and then air blasted to remove any sand particles and water remaining in the joint.
Oregon	N/A	N/A	N/A	N/A	1. The state has very little jointed concrete pavements. The DOT therefore has no Pertinent data.

WET-NONFREEZE ZONE

State	No. of Years of Sealant Use	Types of Sealants Used	Truck Traffic on Sealed Jointed Pavements	Cost/Unit Length of Sealants Used ($/ft)	Observations and Comments About Sealant Use
Mississippi	20	Low Modulus Silicone	High	11.00 (completely installed)	No comments or observations given.

3.3.1 Response from Alaska

Alaska does not technically fall within any of the four climatic zones defined. It stands on its own as an almost permanently frozen zone. Alaska has very little experience with sealants in jointed concrete pavements as nearly all the roads are paved with asphalt concrete. The Fairbanks International Airport and Anchorage International Airport have jointed asphalt concrete pavements though. After the expansion joints in the runway pavements failed in 1985, a lot of research was done on sealants yielding the following results:

1. For the asphaltic concrete pavements, success was first achieved with the sealant Flex 270 manufactured by Koch Asphalt and Materials.
2. Another product that has yielded success as a joint sealant for the asphaltic concrete pavements is Crafco 522.

The observations and recommendations pertinent to this work are:

1. It is easier for the sealants to bond to Portland cement concrete pavements than to asphaltic concrete because it appears they are originally manufactured to be used for PCC joints.
2. The best way to maintain any sealant in the joint is by keeping the joint clean and dry and above 40°F.
3. The sealant must be recessed, that is, kept below grade so that traffic and snow plowing equipment do not damage the seal by pulling the sealant out of the joint.
4. It is recommended that a closed cell backer rod be used in deep joints as this keeps the joints from becoming too strong so as to defeat its own purpose. In

addition, closed cell foam does not hold water, thereby eliminating a host of other problems.

3.3.2 Anomalous Results

The results from Wisconsin and Ohio are contrary to the normal accepted conceptions about joint sealing and practices and therefore need an in depth examination. The fact that these two states also happen to lie in the same climatic region as Delaware makes it even more necessary to delve into the matter.

3.3.2.1.0 The Wisconsin Case

In 1997, the Central Office Research Section of the Wisconsin Department of Transportation (WisDOT) compiled a report entitled "THE GREAT UNSEALING - A Perspective on PCC Joint Sealing". This report was based on studies carried out on over 50 test sections constructed between 1974 to1988. The research was founded on the premise that any joint sealant research has to answer the question why there is the need for sealing and whether the sealing is cost-effective. Joint and sealant studies have to address the issues of whether sealing enhances the pavement performance, and if so, whether it is cost effective. Also if so, what sealant system should be used. A summary of the report is given below.

WisDOT has been studying the effect of PCC joint/crack sealing on total pavement performance for 50 years. In 1953 an accident occurred that challenged the belief that sealing is essential. A jointed plain concrete pavement (JPCP) with 12 meter contraction joint spacing and 6mm wide joints was built on USH 151 in two contiguous counties, Lafayette and Iowa. In both counties the joints and cracks were filled with asphalt based sealant at the time of construction. In Iowa County, the joints were routinely refilled while in Lafayette County, there was no refilling. After 11 years of service, and based upon pavement performance factors i.e. faulting, cracking, spalling, patching, etc., maintenance personnel concluded that it is quite apparent that the omission of the joint sealant resulted in better overall pavement performance than that of the sealed joints. This study indicated that efforts to keep some of the water and incompressibles out of the joints were of no benefit to overall performance. Based somewhat upon the above experience and that of several other pavements where joint filling at the time of construction had inadvertently been omitted, several engineers propounded the question as to whether it was actually necessary to fill contraction joints in PCC pavements. This prompted a more systematic investigation of this subject.

In 1958 several test sections were placed in the southbound lanes of USH 41 in Washington County. This jointed reinforced concrete pavement (JRCP) had dowels. The joint was sawed 6mm wide at 30 meter intervals and filled with hot-poured sealant conforming to ASTM D1190. One experimental section had filled joints, one had alternately filled and unfilled joints and another section had all unfilled joints. By 1966 the investigators were reporting that the unfilled joints exhibited fewer corner cracking and spalling than their filled counterparts.

In 1966 a second larger experimental project was commenced on STH 78 in Columbia County. This seven kilometer stretch of pavement was very similar to USH 41 in design features except that contraction joints were spaced at 24 rather than 30 meters. The joints in the southbound pavement were filled with a hot-poured sealant while the northbound pavement joints were left unfilled. It was also decided in 1966 to expand the objectives of the studies on USH 41 and STH 78 such that what had began as a study of joint performance, became a study of pavement performance. Based upon pavement distress, ride and material integrity as evaluation criteria, it was concluded in 1977, when USH 41 test section was 19 years old, and STH 78 test section was 11 years old that, the omission of a joint sealant at the time of construction had not exerted a significant influence on pavement performance.

These three studies were not however the best designed research projects because they all had the deficiency of the joints not being truly sealed. They actually couldn't possibly be sealed considering the joint spacing, joint shape factor and sealants used. Thus although these studies clearly indicated that the effort to keep some water and incompressibles out of the joint was of no benefit, they did not answer the real question concerning the cost-benefit of truly sealed contraction joints. As such while the WisDOT was certainly convinced that "filled" joints were more harmful than helpful, a careful analysis of truly sealed joints was needed. The studies were certainly not conclusive.

The State in 1974 began a study of pavement performance as influenced by sealed and unsealed contraction joints at various spacing. Over 50 test sections were constructed from 1974 to 1988. The test sections were normally 300 meters long. Five of these pavements which are typical are detailed in this report.

1. Highway 1 - rural
   - JRCP constructed in 1974 with dowels
   - Joint spacing of 6, 12, 18, and 24 meters
   - 22 Test sections with some sealed and some unsealed

- Five sealants used
- Sand subgrade and dense base

2. Highway 2 – rural
    - JPCP constructed in 1983 without dowels
    - Random-skewed joints at 5 meter average spacing
    - 7 Test sections with some sealed and some unsealed
    - Three sealants used
    - Silt subgrade and dense base
3. Highway 3 – rural
    - JPCP constructed in 1983 without dowels
    - Random-skewed joints at 5 meter average spacing
    - 11 Test sections with some sealed and some unsealed
    - Three sealants used
    - Silty-till subgrade and dense base
4. Highway 4 – rural
    - JPCP constructed in 1988 with some test sections doweled and others without dowels
    - Random-skewed joints at 5 meter average spacing
    - 5 Test sections with some sealed and some unsealed
    - One sealant used
    - Silty-clay-loam subgrade, dense base
5. Highway 5 – urban
    - JPCP constructed in 1988 without dowels

- Random-skewed joints at 5 meter average spacing
- 6 Test sections with some sealed and some unsealed
- One sealant used
- Silt/silty-clay subgrade and dense and open graded bases

The seals in Highway 1 were kept perfectly intact for at least 10 years, the originally intended length of the study. The results were summarized and published as follows:

1. When total pavement performance is considered, the results from 10 years of experience indicate that shorter joint spacing (about 6 meters) lead to better pavement performance than longer joint spacing. In addition, the pavement with unsealed joints performed better than the pavement with sealed joints.
2. Performance equality between sealed and unsealed test sections is not enough. The entire costs for maintaining a sealed pavement for 10 years, i.e., from sawing a joint reservoir and sealing it to resealing the joint whenever it is needed amounted to as much as 45 percent more than the cost for a similar unsealed pavement. To justify this cost, one would have to prove either 1. a much greater serviceability (ride) during the pavement's life, 2. much less maintenance, or 3. a significant increase in pavement life. At this time and for this study, there is no basis for believing any of these three justifications is possible.
3. Blow-ups were a major problem in Wisconsin for pavements with 24 and 30 meter joint spacing. The use of closer joint spacing has virtually eliminated blow-ups. Blow-ups are not significantly influenced by joint sealing.

The performance evaluations of the pavements in 1996 are given below. The Highway 1 study was 22 years old; the Highway 2 and Highway 3 study were 12 years old, and the Highway 4 and Highway 5 study were 8 years old. The seals on the latter four pavements projects were not replaced once they failed.

3.3.2.1.1 Distress Evaluation

Wisconsin uses the Pavement Distress Index (PDI) which measures all distresses (extent and severity) and combines them into one index for a true measure of distress. Each distress is weighted to account for that distress' significance on pavement performance. The PDI scale goes from 0 to 100, with 100 being the worst possible.

It was obvious that the pavement in the unsealed test sections on Pavement 1 had less distress than in the sealed sections for joint spacing of 12, 18 and 24 meters. For 6 meter joint spacing the results are reversed. This reversal is indeed significant because it is the shorter joint spacing that is presently used in most states, including Wisconsin. By studying the 22 test sections on Highway 1, in all cases but one, the performance of the unsealed sections was better than the sealed. This anomalous unsealed test section had completely unique behavior from the time of construction. It had significant spalling the first year. The amount of spalling had nothing to do with the lack of joint seal. It resulted from a construction problem. The reinforcing mesh was placed between two lifts of concrete and the mesh migrated during the placement of the second lift. Often this migration caused the mesh to cross the joint area. If the contraction joint sawing did not cut the mesh, the mesh caused joint spalling as the joint opened. This spalling occurred in other sections (mostly the short joint spacing) but was worse in this section than any other. FHWA and Minnesota evaluators independently arrived at the same conclusion. The first half of the test section was in nearly perfect condition at 22 years of age.

To help resolve the issue of whether or not pavements with unsealed joints in pavements with short joint spacing have more distress than pavements with sealed joints, the results from the other four test pavements as given in Table 3.1 are decisive. The average distress index on these projects is either less for unsealed joints than sealed joints or equal. This is an indication that for pavements with short joint spacing there is less distress with unsealed joints than with sealed. A statistical analysis of PDI with everything held constant except joint sealing, comparing sealed and unsealed test sections reveals with 95 percent confidence level that there is no significant difference in PDI. The conclusion was therefore that joint sealing has no significant effect on pavement distress or life.

Table 3.1 Comparison of Pavement Distress Indices (PDI) – Better conditions are indicated by smaller PDI [Shober 1997]

Highway	**Test Age (years)**	**No. of Test Sections**	**Average PDI**	
			Sealed Sections	**Unsealed Sections**
2	12	5 Sealed 2 Unsealed	12	11
3	12	7 Sealed 4 Unsealed	20	17
4	8	2 sealed 2 Unsealed	8	8
5	8	3 Sealed 3 Unsealed	11	11
Weighted Average			15	13

3.3.2.1.2 Ride

Another important factor in assessing total pavement performance according to the WisDOT report is ride experienced by the public. To assess the impact of joint sealing on ride the Wisconsin DOT measured the summer and winter ride on the test sections. The resulting International Roughness Index (IRI) scale goes from zero (perfectly smooth) to over five (rough).

On Highway 1 the summer ride for the unsealed sections is slightly better than for the sealed. If sealing were to make a significant difference it should be during winter in Wisconsin when water can get into the joints, freeze, and then cause the pavement to tent at the joints. The winter ride readings were significantly higher (worse ride) than the summer readings, but the unsealed and sealed sections had an equal ride. The results of the ride readings for the other pavements presented in Table 3.2 were much the same as for Highway 1. In all but one case the unsealed test sections rode equal to or better than the sealed both in summer and winter. As the table indicates, the ride for the undowelled pavements is much lower than for the older doweled pavement on Highway 1. The difference in the ride is due to joint faulting. Interestingly enough the joint faulting data (Table 3.3) often defied traditional wisdom with respect to joint sealing. For State trunk highways, joint faulting is unacceptable when joints are not doweled, whether they are sealed or unsealed. Joints must be doweled.

A statistical analysis of pavement ride comparing sealed and unsealed test sections revealed with 95 percent confidence level that there is no significant difference in ride as a result of joint sealing. It was therefore concluded that joint sealing has no significant effect on ride qualities.

Table 3.2 Comparison of International Roughness Index (IRI) – Smaller IRI indicates better ride [Shober 1997]

Highway	Test Age (years)	No. of Test Sections	Average IRI (m/km)			
			Summer		Winter	
			Sealed	Unsealed	Sealed	Unsealed
2	10	5 Sealed 2 Unsealed	2.01	1.97	2.17	2.01
3 (no dowels)	10	4 Sealed 3 Unsealed	2.75	2.75	2.83	2.91
4	6	2 sealed 2 Unsealed	1.49	1.31	-	-
Weighted Average			2.19	2.12	2.46	2.55

Table 3.3 Joint Faulting for Undowelled Test Sections [Shober 1997]

Highway	Test Age	Unsealed	Sealed
2	10	2.5 mm	3.8 mm
3	10	4.8 mm	5.1 mm
4	7	2.5 mm	2.5 mm
5	8	3.3 mm	3.0 mm

3.3.2.1.3 Materials Integrity

In 1995, the Highway 1 pavement was cored at random locations to determine if joint sealing had an effect on materials integrity. The cores had considerable variation, but the general trend was that the cores from pavements with short joint spacing had no distress. The cores from pavements with long joint spacing generally had significant distress. Joint sealing had no effect on the distress at a joint, however, joint spacing did. The longer the spacing, the more the distress was. Again, blow-ups were a function of joint spacing and not sealing. It was therefore concluded that joint sealing has no significant effect on materials integrity.

3.3.2.1.4 Costs

On the Highway 1 study, the 1974 cost to create a sealed system i.e. second saw cut, backing material, cleaning, and sealing, ranged from 8 to 22 percent of the square meter cost for a pavement with an unsealed system. When the costs for maintaining the joints in a sealed condition for 10 years were added, the pavement with the sealed joint system cost up to 45 percent more than the similar unsealed pavement. Some newer sealants now have a much larger extension range than the older sealants, and sealing costs are lower now percentage-wise. Assuming it would cost $1.32 per square meter for the second cut, cleaning, backer, and sealant, Wisconsin saves 2,800,000 dollars a year by not sealing a newly constructed PCC pavement joints. If a sealed system were to be maintained, the joints in existing pavements would have to be resealed say every eight years. This resealing would amount to over 3,200,000 dollars annually. Summing the two, it appears that Wisconsin saves 6,000,000 dollars a year by not trying to have a sealed system. This has four profound impacts, namely:

1. There is no loss in pavement performance.
2. It makes PCC more competitive.
3. It allows for more highway rehabilitation and construction.
4. It reduces customer inconvenience related to joint resealing.

3.3.2.1.5 Explanations

It appears from the Wisconsin study that the old axiom that water and incompressibles must be kept out of a pavement joint in order to get good performance is not true. The explanations for the seen improved or at least equal performance due to unsealed joints could be as follows:

1. Stress Concentrations - In the nineteen sixties Wisconsin engineers noted that filled joints soon became partially sealed. Even truly sealed joints deteriorate and became partially sealed. It has been postulated that the partially sealed condition allows incompressible material to enter the joint at the discrete locations of sealant failure. When the pavement expands the expansion force is concentrated entirely at the discrete locations of the incompressibles, causing extreme stress concentrations with the associated spalls and corner cracking (crows-foot cracking). Wisconsin's unsealed joints are 3 - 6 mm wide. They become uniformly filled full with fine incompressible material except at the top 25 mm or so which is kept clear by traffic. When the pavement expands the stress is uniformly distributed across the entire pavement cross section. This uniform stress can only amount to 7000 - 14,000 kPa maximum, well below the compressive strength of the concrete.
2. Incompressible Locations - The incompressibles are not near the top of the joint so there is no stress at the top joint edge in hot weather either due to expansion and/or curling. In addition, no large incompressibles can get into the narrow joint to cause stress concentrations.
3. Construction and Maintenance - The initial joint sawing can cause joint spalling or induce stresses which lead to spalling. In order to truly have a sealed system, resealing is required. The various operations involved in resealing itself often cause some joint spalling. In addition, resealing can result in sealant getting on

the pavement surface which causes a bump and lowers ride quality. Resealing can be aesthetically unpleasant. The wide joint reservoir for the sealants causes tire noise and can affect ride.

4. Funneling Water - Wisconsin's narrow, unsealed joints are actually quite impermeable in warm weather. The fine incompressibles causes a tight seal (water will stand in a joint long after rain). In winter the base is frozen so no water can get into the structure. A truly sealed system will soon begin to have sealant failures. These result in a funneling effect which allows more water to enter the joint than would occur with a narrow unsealed joint. This funneling action occurs because the joint is widened at the top to make a reservoir and the sealant is generally recessed. Thus when the sealant fails, a natural funnel is created to intercept any direct water into the pavement structure.

WisDOT's research indicates that the best overall PCC performance is achieved with narrow, unsealed joints. The next best performance is with sealed joints. The worst performance results from partially sealed or filled joints. Unfortunately, every sealed joint will decay into a partially sealed joint unless a rigid resealing regime is adhered to. Even with such a regime, the pavement performance will not equal that of an unsealed system.

3.3.2.2.0 The Ohio Case

3.3.2.2.1 Introduction

The Ohio experimental project consists of the construction by a contractor, and the monitoring and evaluation to date of a stretch of a four-lane highway by a team from the College of Engineering at the University of Cincinnati, in cooperation with Ohio Department of Transportation (ODOT) and the U.S. Department of Transportation (US DOT), Federal Highway Administration (FHWA). The experimental design of this project was developed in 1997 by the FHWA and ODOT to provide data for evaluation of the performance of various joint seals and joint configurations in the wet-freeze climate, in which, coincidentally, the state of Delaware also falls. Fifteen combinations of materials and joint configurations, including unsealed control sections, are used in the experiment. The purpose of these pavements is to duplicate and compliment similar sections constructed in other states under the SHRP SPS-4 experiment. The full report is compiled in I0annides et al. [2002].

The test pavement in this report is divided into fifteen test sections. Each of the test sections is typically 183m (600 ft) in length although some longer sections are also included. Each test section contains about thirty joints. In accordance with the experimental design, each of the fifteen chosen material-joint configuration combination was replicated, two of these involving unsealed joints. For each case, one replicate is located on the eastbound lanes and the other on the westbound lanes. The eastbound lanes were constructed during the 1997-1998 construction season while the westbound lanes were constructed during the 1998-1999 construction season. The objectives established in constructing the test sections were:

1. To assess the effectiveness of a variety of joint sealing practices employed after the initial sawing of joints, and to examine their repercussion in terms of reduced construction time and life cycle costs
2. To identify those materials and procedures that are most cost effective
3. To determine the effect of joint sealing techniques on pavement performance

3.3.2.2.2 Description of Project and Weather Conditions of Project Location

The test site under investigation is a 3.3 km (2.0 mile) section of a new 10.5 km (6.5 mile) four lane divided highway in Athens County, southeast Ohio. The experimental pavement is part of the 10.5 km stretch under reconstruction. The project as mentioned earlier lies in the Wet-Freeze zone where local mean annual precipitation is 980 mm (38.6 in.), out of which 533 mm (21 in.) usually accumulates between April and September. At higher elevations, in Athens County, winters are cold and snowy, with a mean annual snowfall of 447 mm (17.6 in). In the valleys, although it is also frequently cold too, intermittent thaws prevent a long snow cover. During the winter months, average temperature is 0°C (32°F), and the average daily minimum temperature is -6°C (21°F). The average summer temperature is 22°C (71°F) with an average daily maximum temperature of 29°C (85°F). The reconstructed four-lane highway has a design period of twenty years, with a current (1993) average daily traffic (ADT) of 7820 and design year 2013 ADT of 10950. Design traffic level is eleven million Equivalent Single Axle Loads (ESAL), and the truck percentage is 9 percent. The pavement cross-section consists of a

250 mm (10-in.) plain, jointed, wire-reinforced Portland cement concrete (PCC) slab placed over a 100 mm (4 in.) crushed aggregate free draining base layer. The base layer is constructed over a 150 mm (6 in.) crushed aggregate subbase, which in turn rests predominantly on silty clay local subgrade.

The highway consists of two 3.7 m (12 ft) wide lanes having tied PCC shoulders in both the eastbound and westbound directions. On the inner (abutting the median) and outer sides of the pavement, the shoulders are 1.2 and 3 m (4 and 10 ft.) wide respectively. Transverse joints, spaced every 6.4 m (21 ft), are fitted with 38mm (1.5 in.) epoxy-coated steel dowels 460 mm (18 in.) long. The dowels are supported on baskets and are placed at 305 mm (12 in.) centers, starting at 150 mm (6 in.) from the shoulder joint. The longitudinal center line and shoulder joints are tied with 16 mm (0.625 in.) diameter by 760 mm (30 in.) long deformed steel bars spaced every 760 mm (30 in.).

3.3.2.2.3 Types, Names and Joint Configuration of Sealants

Tables 3.4 and 3.5 present the types and names of sealants, as well as the joint configurations for each test station for the eastbound and westbound lanes respectively. Table 3.6 describes the joint sealant failure and distress types.

Six joint configurations were used. Configurations 1, 3, and 4 were 9.5 mm, 6.35 mm an 3.17 mm (3/8, 1/4, and 1/8 inch) wide plus or minus 1.59 mm (1/16 inch) respectively. Configurations 1, 3 and 5 received secondary cuts, and backer rods were placed in configurations 1, 3 and 4 only. Backer rods were typically 3.17 mm (1/8 inch) larger than the joint opening. Configurations 2 and 6 were unsealed

3.17 mm (1/8 inch) and 9.5 mm (3/8 inch) plus or minus 3.17 mm (1/16 inch) wide respectively. All compression seal joints had joint configuration 5 which was 9.5 mm (3/8 inch) plus or minus 1.59 mm (1/16 inch) wide.

Table 3.4 Sealant Type, Sealant Name and Joint Configuration Eastbound [Ioannides et al. 2002]

Type	**Sealant**	**Joint Configuration**	**No. of Joints**
Self-leveling silicone	Crafco 903-SL	1	29
Self-leveling silicone	Crafco 903-SL	4	33
Self-leveling silicone	Dow 890-SL	3	29
Self-leveling silicone	Dow 890-SL	4	29
Self-leveling silicone	Dow 890-SL	1	28
Non-sag silicone	Crafco 902	1	29
Non-sag silicone	Dow 888	1a	57
Non-sag silicone	Dow 888	1b	29
Hot-pour	Crafco 221	1	29
Hot-pour	Crafco 444	1	76
Compression Seal	Delastic V-687	5	29
Compression Seal	Watson Bowman WB-687	5	27
Compression Seal	Techstar W-050	5	29
Unsealed	No Sealant	6	29
Unsealed	No sealant	2	28

Table 3.5 Sealant Type, Sealant Name and Joint Configuration Westbound [Ioannides et al. 2002]

Type	Sealant	Joint Configuration	No. of Joints
Self-leveling silicone	Crafco 903-SL	1	29
Self-leveling silicone	Crafco 903-SL	1	29
Self-leveling silicone	Crafco 903-SL	4	28
Self-leveling silicone	Dow 890-SL	3	29
Self-leveling silicone	Dow 890-SL	1	28
Self-leveling silicone	Dow 890-SL	4	57
Non-sag silicone	Dow 888	1	28
Non-sag silicone	Dow 888	1	29
Hot-pour	Crafco 221	1	76
Hot-pour	Crafco 444	1	33
Compression Seal	Delastic V-687	5	29
Compression Seal	Watson Bowman WB-812	5	28
Compression Seal	Techstar W-050	5	29
Unsealed	No Sealant	2	126
Unsealed	No Sealant	6	29

3.3.2.2.4 Description of Sealant Failure and Distresses

A description of joint sealant failure and distress modes for the different sealant types is described in Table 3.6.

Table 3.6 Description of Joint Sealant Failure and Distress Types [Ioannides et al. 2002]

DISTRESS	
Field-Molded Sealants	
Partial depth adhesion loss	Separation of the sealant from one or both edges of the joint, but the separation does not extend through the entire sealant depth.
Partial depth spalling	Cracking, breaking, or chipping of a PCC slab from one or both edges within 0.6 m (2 ft) of the joint which does not extend vertically through the depth of the joint sealant.
Partial depth Cohesion loss	Splitting of the sealant due to elongation which exceeds the tensile strength of the sealant, but the splitting does not extend vertically through the entire sealant depth. It may be either tensile failure or failure due to bubbles contained within the sealant.
Stone intrusion	The embedment of stones with diameter grater than 6 mm (0.25 in) into the seal material such that they are incapable of being easily removed.
Preformed Compression Seals	
Partial depth adhesion loss	Separation of the sealant from one or both edges of the joint, but the separation does not extend through the entire sealant depth.
Partial depth spalling	Cracking, breaking, or chipping of a PCC slab from one or both edges within 0.6 m (2 ft) of the joint which does not extend vertically through the depth of the joint sealant.
Stone intrusion	The embedment of stones with diameter grater than 6 mm (0.25 in) into the seal material such that they are incapable of being easily removed.
Surface extrusion	The neoprene seal distends above the pavement surface as a result of twisting or high placement.
Full depth adhesion loss	The sealant has separated from one or both edges of the joint allowing infiltration of moisture and incompressibles.
Full depth spalling	Cracking, breaking, or chipping of a PCC slab from one or both edges within 0.6 m (2 ft) of the joint that vertically extends below the depth of the joint sealant.
Full depth Cohesion loss	The sealant has split vertically through its entire depth allowing infiltration of moisture and incompressibles.
Sunken seal	Sealant has completely separated from both edges and sunken into the joint leaving a low area that is not watertight.
Preformed Compression Seal	
Full depth adhesion loss	Compression seal has separated from one or both edges of the joint, allowing infiltration of moisture and/or incompressibles.
Full depth spalling	Cracking, breaking, or chipping of a PCC slab from one or both edges within 0.6 m (2 ft) of the joint that vertically extends below the depth of the joint sealant.
Twisted/rolled seal	Condition in which the neoprene seal is twisted, rolled, or turned in the joint leaving the surface edges of the seal at different elevations.
Compression set	When the neoprene web structure loses its ability to exert outward pressure as a result of being in compression for a long duration.
Gap	Joint opens wider than the compression seal is able to span, allowing stones to become lodged between the edge of the compression seal and the edge of the joint.
Sunken seal	Seal has sunken into joint leaving a low area that is not watertight.

The sealant inspection plan involved the recording of distress occurring in the immediate vicinity of joints which may be indicative of joint seal inefficiency or failure to determine whether the sealing of transverse joints has an effect on concrete pavement performance. In the context of development of cracks in jointed reinforced concrete slabs, it is assumed by the designer that a crack will form generally at the center of the slab. Reinforcing steel is thus introduced to prevent 'objectionable cracking'. Monitoring of transverse cracks at the test site is therefore aimed at assessing whether cracks become objectionable from a functional viewpoint, and if so, whether this crack development is related to sealant performance in any way.

3.3.2.2.5 Effectiveness Ranking of Sealants

Based on these studies, the sealants were ranked according to their effectiveness level. These ranking are summarized in Tables 3.8 through 3.13 for the year 2000 and 2001 surveys. The rating used for these rankings are given in Table 3.7.

Table 3.7 Rating Table [Ioannides et al. 2002]

Rating	Overall Effectiveness Level (%)
Very Good (VG)	90 to 100
Good (G)	80.0 to 89.9
Fair (F)	65.0 to 79.9
Poor (P)	50.0 to 64.9
Very Poor (VP)	0 to 49.9

The results of this study so far suggest that unsealed joints are no more likely to fail than joints sealed with hot-applied, silicone and even some compression seals.

Table 3.8 Effectiveness Rankings for Eastbound Lane Treatments during the October 2000 Survey [Ioannides et al. 2002]

Sealant Type	Description	% Eff in EBMR00	% Eff Rank	% Eff in EBOC00	% Eff Rank	% Deterioration	Rank of % Deterioration
Silicone	Crafco 903-SL (l)	51.9 (P)	7	48.1(VP)	6	3.8	8
	Crafco 903-SL (4)	24.2 (VP)	12	6.7 (VP)	12	17.5	2
	Crafco 903-SL (3)	67.5 (F)	5	55.8 (P)	5	11.7	3
	Dow 890-SL (4)	55.0 (P)	6	12.5 (VP)	11	42.5	1
	Dow 890-SL (1)	67.8 (F)	4	63.6 (VP)	4	4.2	7
	Dow 890-SL (1)	40.8 (VP)	10	37.2 (VP)	9	3.6	9
	Dow 888 (1)	50.0 (P)	8	40.6 (VP)	8	9.4	4
	Dow 888 (1)	48.9 (VP)	9	41.1 (VP)	7	7.8	5
Hot-Applied	Crafco 221 (1)	71.9 (F)	3	70.6 (F)	3	1.3	11
	Crafco 441 (1)	9.7 (VP)	13	6.1 (VP)	13	3.6	9
Compression	Delastic V-687 (5)	95.3 (VG)	1	97.2 (VG)	2	-1.9	12
	Watson Bowman 812 (5)	95.3 (VG)	1	97.8 (VG)	1	-2.5	13
	Techstar W-050 (5)	32.8 (VP)	11	26.9 (VP)	10	5.9	6

EBMR00 - Eastbound March2000

EBOC00 – Eastbound October 2000

Table 3.9 Eastbound Lane Treatments during the January 2001 Survey [Ioannides et al. 2002]

Sealant Type	Description	% Eff in EB)C00	% Eff Rank	% Eff in EBJN01	% Eff Rank	% Deterioration	Rank of % Deterioration
Silicone	Crafco 903-SL (l)	48.1(VP)	6	62.8 (P)	6	-14.7	8
	Crafco 903-SL (4)	6.7 (VP)	12	56.1 (P)	9	-49.4	12
	Dow 890-SL (3)	55.8 (P)	5	62.2 (P)	7	-6.4	7
	Dow 890-SL (4)	12.5 (VP)	11	65.0 (F)	5	-52.5	13
	Dow 890-SL (1)	63.6 (VP)	4	79.7 (F)	3	-16.1	10
	Crafco 902 (1)	37.2 (VP)	9	35.8 (VP)	11	1.4	4
	Dow 888 (1)	40.6 (VP)	8	56.1 (P)	9	-15.5	9
	Dow 888 (1)	41.1 (VP)	7	60.8 (P)	8	-19.7	11
Hot-Applied	Crafco 221 (1)	70.6 (F)	3	75.3 (F)	4	-4.7	5
	Crafco 441 (1)	6.1 (VP)	13	11.1 (VP)	13	-5.0	6
Compression	Delastic V-687 (5)	97.2 (VG)	2	94.2 (VG)	2	3.0	2
	Watson Bowman 687 (5)	97.8 (VG)	1	95.0 (VG)	1	2.8	3
	Techstar W-050 (5)	26.9 (VP)	10	21.9 (VP)	12	5.0	1

EBJN01 - Eastbound January 2001

EBOC00 – Eastbound October 2000

Table 3.10 Eastbound Lane Treatments during the October 2001 Survey [Ioannides et al. 2002]

Sealant Type	Description	% Eff in EBJN01	% Eff Rank	% Eff in EBOC01	% Eff Rank	% Deterioration	Rank of % Deterioration
Silicone	Crafco 903-SL (l)	62.8 (P)	6	57.8 (P)	5	5.0	7
	Crafco 903-SL (l)	56.1 (P)	9	11.9 (VP)	12	44.2	1
	Crafco 903-SL (4)	62.2 (P)	7	56.9 (VP)	6	5.3	6
	Dow 890-SL (3)	65.0 (F)	5	42.5 (VP)	9	22.5	2
	Dow 890-SL (1)	79.7 (F)	3	70.8 (F)	4	8.9	5
	Dow 890-SL (4)	35.8 (VP)	11	31.1 (VP)	10	4.7	8
	Dow 888 (1)	56.1 (P)	9	46.7 (VP)	8	9.4	4
	Dow 888 (1)	60.8 (P)	8	48.9 (VP)	7	11.9	3
Hot-Applied	Crafco 221 (1)	75.3 (F)	4	79.2 (F)	3	-3.9	13
	Crafco 441 (1)	11.1 (VP)	13	9.4 (VP)	13	1.7	10
Compression	Delastic V-687 (5)	94.2 (VG)	2	94.4 (VG)	1	-0.2	12
	Watson Bowman 812 (5)	95.0 (VG)	1	94.4 (VG)	1	0.6	11
	Techstar W-050 (5)	21.9 (VP)	12	18.6 (VP)	11	3.3	9

EBJN01 - Eastbound January 2001

EBOC01 – Eastbound October 2001

Table 3.11 Effectiveness Rankings for Westbound Lane Treatments during the October 2000 Survey [Ioannides et al. 2002]

Sealant Type	Description	% Eff in WBMR00	% Eff Rank	% Eff in WBOC00	% Eff Rank	% Deterioration	Rank of % Deterioration
Silicone	Crafco 903-SL (1)	95.0(VG)	7	97.8 (VG)	5	-2	11
	Crafco 903-SL (l)	76.7 (F)	11	78.9 (F)	10	-2.2	9
	Crafco 903-SL (4)	88.6 (G)	9	90.8 (VG)	9	-2.2	9
	Dow 890-SL (3)	99.4 (VG)	2	99.7 (VG)	2	-0.3	6
	Dow 890-SL (1)	98.1 (VG)	4	97.2 (VG)	6	0.9	5
	Dow 890-SL (4)	86.1 (G)	10	56.7 (P)	11	29.4	2
	Dow 888 (1)	99.2 (VG)	3	96.4 (VG)	7	2.8	4
	Dow 888 (1)	97.8 (VG)	5	98.3 (VG)	4	-0.5	8
Hot-Applied	Crafco 221 (1)	49.7 (VP)	13	46.1 (VP)	12	3.6	3
	Crafco 441 (1)	89.2 (G)	8	96.1 (VG)	8	-6.9	13
Compression	Delastic V-687 (5)	95.6 (VG)	6	98.6 (VG)	3	-3.0	12
	Watson Bowman 812 (5)	99.7 (VG)	1	100.0 (VG)	1	-0.3	6
	Techstar W-050 (5)	69.7 (F)	12	26.7 (VP)	13	43.0	1

WBMR00 - Westbound March 2000

WBOC00 - Westbound October 2000

Table 3.12 Effectiveness Rankings for Westbound Lane Treatments during the January 2001 Survey [Ioannides et al. 2002]

Sealant Type	Description	% Eff in WBOC00	% Eff Rank	% Eff in WBJN01	% Eff Rank	% Deterioration	Rank of % Deterioration
Silicone	Crafco 903-SL (l)	97.8 (VG)	5	96.1 (VG)	8	1.7	3
	Crafco 903-SL (l)	78.9 (F)	10	78.6 (F)	11	0.3	5
	Crafco 903-SL (4)	90.8 (VG)	9	95.8 (VG)	9	-5.0	11
	Dow 890-SL (3)	99.7 (VG)	2	97.8 (VG)	6	1.9	2
	Dow 890-SL (1)	97.2 (VG)	6	96.7 (VG)	7	0.6	4
	Dow 890-SL (4)	56.7 (P)	11	79.2 (F)	10	-22.5	13
	Dow 888 (1)	96.4 (VG)	7	99.7 (VG)	1	-3.3	10
	Dow 888 (1)	98.3 (VG)	4	98.1 (VG)	4	0.2	7
Hot-Applied	Crafco 221 (1)	46.1 (VP)	12	57.8 (P)	12	-11.7	12
	Crafco 441 (1)	96.1 (VG)	8	98.1 (VG)	4	-1.9	9
Compression	Delastic V-687 (5)	98.6 (VG)	3	99.7 VG)	2	-1.1	8
	Watson Bowman 812 (5)	100.0 (VG)	1	99.7 VG)	2	0.3	5
	Techstar W-050 (5)	26.7 (VP)	13	14.2 (VP)	13	12.5	1

WBOC00 - Westbound October 2000

WBJN01 –Westbound January2001

Table 3.13 Effectiveness Rankings for Westbound Lane Treatments during the October 2001 Survey [Ioannides et al. 2002]

Sealant Type	Description	% Eff in WBJN01	% Eff Rank	% Eff in WBOC01	% Eff Rank	% Deterioration	Rank of % Deterioration
Silicone	Crafco 903-SL (1)	96.1 (VG)	8	95.8 (VG)	6	0.3	10
	Crafco 903-SL (1)	78.6 (F)	11	72.2 (F)	10	6.4	6
	Crafco 903-SL (4)	95.8 (VG)	9	84.7 (G)	9	11.1	3
	Dow 890-SL (3)	97.8 (VG)	6	99.4 (VG)	1	-1.6	13
	Dow 890-SL (1)	96.7 (VG)	7	96.7 (VG)	5	0.0	12
	Dow 890-SL (4)	79.2 (F)	10	43.9 (VP)	11	35.3	1
	Dow 888 (1)	99.7 (VG)	1	90.8 (VG)	8	8.9	5
	Dow 888 (1)	98.1 (VG)	4	97.8 (VG)	3	0.3	10
Hot-Applied	Crafco 221 (1)	57.8 (P)	12	42.8 (VP)	12	15.0	2
	Crafco 441 (1)	98.1 (VG)	4	92.5 (VG)	7	5.6	7
Compression	Delastic V-687 (5)	99.7 VG)	2	97.2 (VG)	4	2.5	8
	Watson Bowman 812 (5)	99.7 VG)	2	97.8 (VG)	2	1.9	9
	Techstar W-050 (5)	14.2 (VP)	13	4.4 (VP)	13	9.8	4

WBOC01 - Westbound October 2001

WBJN01 –Westbound January 2001

3.4 SHRP-H-355 Test Sections

3.4.1 Introduction

This project was carried out by ERES Consultants and involved the resealing of five test sites, twelve sealant materials, four installation methods and a total of 1600 joints. Test sites were located on moderate to high volume roadways in the dry-nonfreeze (Arizona), wet-nonfreeze (South Carolina), dry-freeze (Colorado) and two wet-freeze sites (Iowa and Kentucky). The test sections in Iowa had short joints while those in Kentucky had long joints to enable comparison between the effects of long and short jointed pavements. Field performance data was collected for 82 months [FHWA 137 1999].

3.4.2 Sealants Used in Study

The sealants used in this study are summarized in Table 3.14 and included six rubberized asphalt sealants, two self-leveling and one non-self-leveling silicone sealants installed at four of the five test sites. The rest are two rubberized asphalt sealants installed in the dry-nonfreeze region.

Table 3.14 Sealant Materials Used

Sealant Name	Sealant Type
Crafco Roadsaver 231	Low-modulus ASTM D 3405 rubberized asphalt sealant
Koch 9005	ASTM D 3405 rubberized asphalt sealant
Koch 9030	Low-modulus ASTM D 3405 rubberized asphalt sealant
Meadows Sof-Seal	Low-modulus ASTM D 3405 rubberized asphalt sealant
Crafco Roadsaver 221	ASTM 3405 rubberized asphalt sealant (Arizona site only)
Meadows Hi-Spec	ASTM D 3405 rubberized asphalt sealant (Arizona site only)
Dow Corning 888	Non-self-leveling silicone sealant
Dow Corning 888-SL	Self-Leveling silicone sealant
Mobay Baysilone 960-SL	Self-Leveling silicone sealant
Crafco Roadsaver 903-SL	Self-leveling silicone sealant
Mobay Baysilone 960	Non-self leveling silicone sealant
Koch 9050	Self-leveling one part polysulfide

3.4.3 Joint Configuration and Failure Criteria

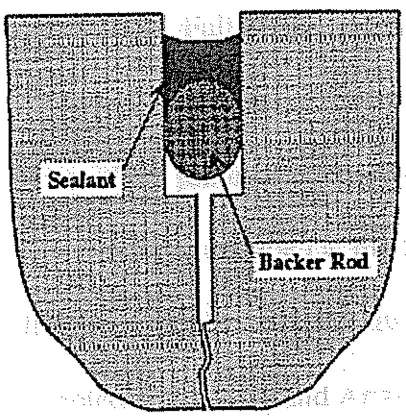
The joint preparation and sealant installations methods used are presented in Figure 2. There were four configurations in all. The data was collected on a foot by foot basis in this study and included:

1. Partial-depth and full-depth adhesion loss on the approach and leave side
2. Partial-depth and full-depth spall failure on the approach and leave side
3. Overband wear on approach and leave side
4. Stone intrusion
5. Partial-depth and full-depth cohesive failure

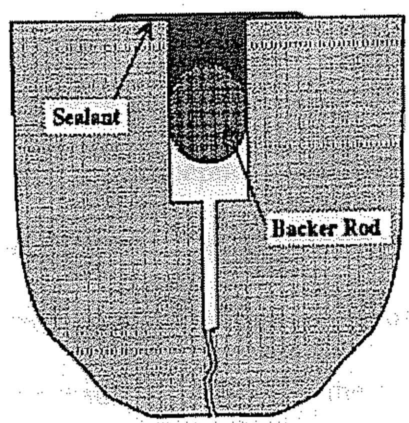
The approach and leave side of the joint correspond to the left and right sides of the joint. The failure criteria used in this study are described as follows:

1. Joints classified as having full-depth failure are those in which the sealant has separated from the side walls or spalled sufficiently to allow moisture and/or debris to pass the seal and enter the joint.
2. The definition of a failed joint is one that allows moisture or debris past the sealant for at least fifty percent of the joint length.

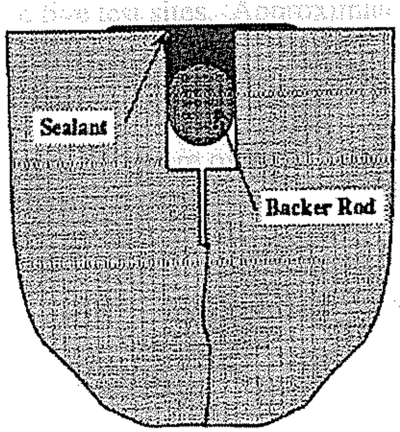
Figure 2 Joint Configurations [Evans and Romine 1993]



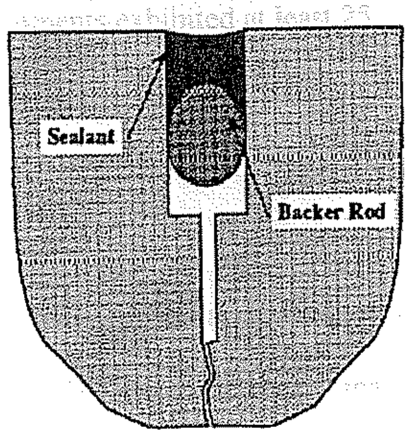
Configuration 1 - Joint Sawed & Sealant Recessed



Configuration 2 - Joint Sawed & Sealant Overbanded



Configuration 3 - Joints Plowed & Sealant Overbanded



Configuration 4 - Joints sawed & Sealant Flush-filled

3.4.4 Summary of Results

Adhesion loss and spall failure were the major distresses after 18 months. Partial-depth adhesion loss ranged from 3.2 mm (0.125 inch) to 60 percent of the sealant thickness. The average depth of partial-depth adhesion loss was approximately half the sealant thickness. Spall-related failures occurred predominantly in the colder states i.e. Iowa and Colorado. Partial-depth spalls in these states were typically three to seven times more frequent than full depth spalls. A common feature that was also noted was the reduction in the thickness of the overbanded sealant material.

Full-depth failure in inches is summarized in Table 3.15. These values include both spall and adhesion failure. After 18 months however, approximately 95 percent of the joints were in good to excellent condition. Major exceptions were the hot-applied sealants installed at the South Carolina site using configuration 3. In these joints, full-depth failure averaged between 11.6 and 41.9 percent. Low intensity stone intrusion was noted at the Iowa and Arizona sites, but these were not sufficient to affect the sealant performance.

After 82 months a significant amount of overall seal failure developed at the five test sites. Approximately 52 percent of the treatments exhibited at least 25 percent failure. The predominant distresses were adhesion loss and spall failure. Other key findings are over the study period with respect to sealant performance were as follows:

A significant amount of overall seal failure developed at the five test sites. Approximately 52% of the treatments exhibited at least 25% failure, the predominant distresses being adhesion loss and spall failure. Other key findings over the study period are:

1. Much higher amounts of partial- and full-depth spalling occurred in the colder regions on joints containing silicone sealants than on those containing standard, recessed rubberized asphalt sealant.
2. Joints filled with silicone and hot-applied sealants experienced less partial- and full-depth spall failure in the warmer regions.
3. When installed in identically prepared joints using the standard, recessed configuration, the silicone sealants developed significantly less partial-depth adhesion failure than the hot-applied sealants.
4. In the standard, recessed configuration, the silicone sealants outperformed all hot-applied sealants in full-depth adhesion failure at three sites. Although the Koch 9005 hot-applied sealant exhibited the same full-depth adhesiveness at two sites, the remaining hot-applied materials developed more adhesion failure.
5. When the same installation methods are used, the evaluated silicone sealants are more cost-effective on long term resealing projects than the hot-applied sealants.
6. Based on 60 joint seals at Iowa site, no significant differences in sealant adhesion failure, spall failure, and overall failure were found to exist among primed and unprimed joints containing the same sealant. The same was true at the Kentucky site with the Koch 9005 asphalt sealant.
7. The ASTM D 3583 tensile adhesion test correlated well with adhesion failure in the field, in both the hot-applied and the silicone sealants. Performance-based

acceptance testing of silicone sealants using non-immersed ASTM D 3583 tensile adhesion test is recommended.

8. Overall seal life failure and estimated service life related well with the ASTM D 113 maximum elongation and the ASTM D 3583 tensile adhesion test for hot-applied sealants and are recommended for use as an indicator of field performance.

Table 3.15 Summary of Full-Depth Failure for All Sites [Evans and Romine 1993]

Sealant Material	Configuration	Total Joints Installed	Percent of Full-Depth Failure After 18 Months				
			Arizona	South Carolina	Colorado	Iowa	Kentucky
Koch 9005	1	100	0.1	2.2	2.9	0.5	0.5
	2	100	0.0	0.2	0.3	0.1	0.0
	3	60	-	19.2	-	0.3	0.1
	4	40	0.5	-	0.3	-	-
Crafco Roadsaver 231	1	100	1.6	0.0	1.7	0.7	0.6
	2	100	0.0	0.0	1.9	0.4	0.4
	3	60	-	5.3	-	0.1	0.0
	4	40	1.4	-	1.0	-	-
Meadows Sof-Seal	1	80	-	1.2	3.8	3.1	1.9
	2	80	-	1.7	7.3	0.7	2.4
	3	60	-	11.6	-	1.5	0.3
	4	20	-	-	6.2	-	-
Koch 9030	1	80	-	4.6	10.1	0.4	1.9
	2	80	-	3.8	7.3	3.2	4.4
	3	60	-	41.9	-	3.0	0.4
	4	20	-	-	6.2	-	-
Meadows Hi-Spec	1	20	0.2	-	-	-	-
	2	20	0.1	-	-	-	-
	4	20	0.1	-	-	-	-
Crafco Roadsaver 221	1	20	0.6	-	-	-	-
	2	20	0.0	-	-	-	-
	4	20	1.2	-	-	-	-
Dow 888	1	100	0.1	0.6	1.3	1.0	3.3
Dow 888-SL	1	100	0.2	0.2	1.0	1.5	0.2
Mobay 960-SL	1	100	0.0	0.9	2.2	3.6	1.3
Mobay 960	1	20	-	-	-	1.0	-
Crafco 903-SL	1	20	0.1	-	-	-	-
Koch 9050	1	30	-	-	0.8	-	0.0
Dow 888 with Primer	1	10	-	-	-	0.8	-
Dow 888-SL with Primer	1	10	-	-	-	0.4	-
Koch 9005 with Primer	1	10	-	-	-	-	0.1

CHAPTER 4

QUALITATIVE ANALYSIS

4.1 Introduction

There is a variety of sealant materials used to seal rigid pavement joints. The choice of material depends to some extent on the pavement use, i.e. for airfield pavements or for highways. There are currently no performance-based specifications developed for rigid pavement joint sealants. It is thus impossible to objectively select the most appropriate sealant for any specific given set of conditions. Further more, although the visual inspection of joint systems and sealants to determine sealant performance is highly subjective and inappropriate, there are currently no testing procedures available for verifying sealant performance in the field. Based on the case studies and LTPP data, an attempt will be made in this chapter to qualitatively analyze the factors affecting sealant performance and failure modes.

4.2 Factors Affecting Sealant Performance

The factors which affect the way any particular sealant will perform are many. The most significant among them are:

1. Bonding between sealant and the side walls (adhesion)
2. Sealant reservoir shape (shape factor)

3. Properties of the sealant (cohesion)
4. Movement of the joint
5. Proper workmanship
6. Environmental Factors (Weatherability, compatibility and debris intrusion)

Adhesive and cohesive properties are the two most important properties of a joint sealant. The ideal sealant must adhere to the side walls of the joint reservoir and should maintain its resilience at all temperatures i.e. should neither harden during cold temperatures nor soften during hot weather. Currently however, all available concrete pavement joint sealants exhibit differing degrees of adhesion and cohesion.

4.3 Analysis of Adhesive Failures

Adhesion is the ability of the sealant to adhere to the concrete i.e. the joint reservoir walls. Both initial and long-term adhesion is equally important. Joint movement comprises of two components. These are shrinkage movement due to curing and thermal expansion/contraction. The elongation properties of the sealant become critical when the joint opens up with the initial shrinkage of the curing concrete. The depth of the joint sealant has considerable effect on the stresses and strains applied to the sealant due to the joint movement. A deep joint leads to high stresses along the sealant/joint wall interface while a shallow joint leads to lower stresses. These two phenomena are illustrated in Figures 3 and 4 respectively.

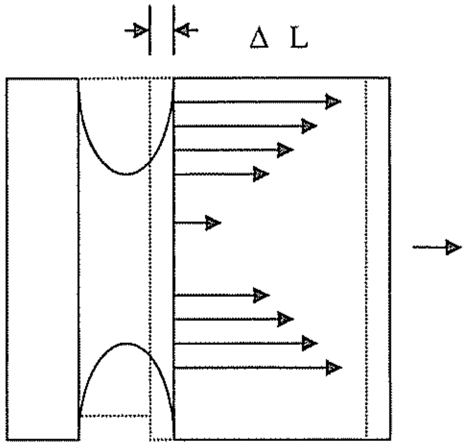


Figure 3 Sealant Stresses for a Deep Joint Resulting from Pavement Contraction [Biel et al. 1999]

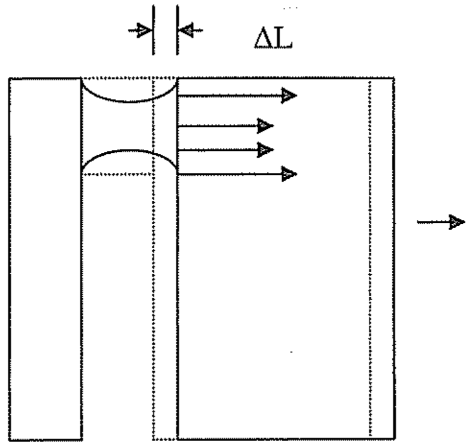


Figure 4 Sealant Stresses for a Shallow Joint Resulting from Pavement Contraction [Biel et al. 1999]

When the concrete pavement cools down in the evening, the joints open up as a function of the slab length. These joint seal openings due to temperature differentials are estimated based on the AASHTO design guide (1986) that adopted the following equation to predict joint opening:

$$\Delta L = C \,.\, JS \,.\, [\, (\alpha_c .\, T) + Z]$$

where: ΔL = joint opening caused by temperature changes and drying shrinkage of PCC (centimeters or inches)

α_c = thermal coefficient of contraction of the PCC slab (/^{o}C or /^{o}F)

T = temperature range from PCC placement to minimum temperature (/^{o}C or /^{o}F)

Z = drying shrinkage coefficient of the PCC slab(neglect for resealing projects)

C = adjustment factor for friction between slab and subbase : 1.0 for natural clay subgrade, 0.80 for granular subbase, and 0.65 for stabilized subbase

JS = joint spacing (centimeters or inches)

From this equation, joint opening is a function of joint spacing and the temperature range from PCC placement to minimum temperature. The greater the joint spacing and this temperature range the larger the joint opening. When the pavement temperature rises, it expands and the joints reduce in width. Vice versa, when pavement temperature is low, the pavement contracts, thus causing the joints to open. For effective sealing, the sealant must elongate to the same extent as the joint opening. Very often however, maximum elongation of sealants used for resealing does not always equal the maximum joint opening. If sealants were installed at annual highest pavement temperature, the maximum elongation would be equal to the maximum joint opening. If sealants were installed at the average of the annual high and low temperatures i.e. the medium temperature, maximum elongation of resealing material would equal half of the maximum joint opening. Restricting the temperature to lower than a selected appropriate temperature at the time of resealing construction can minimize sealant damage due to the excessive elongation of sealant. Consideration of pavement temperature however at the time of sealant installation during the design status is not always practical. Selection of the temperature as the maximum annual temperature is therefore conservative and is considered as design temperature range.

At low pavement temperatures when the joints widen, there is a tendency for the sealant to separate from the receding joint reservoir walls and cause adhesive failure. The bigger and more erratic this joint opening is the greater the tendency for adhesive failure. Thus it may be inferred that adhesive failures are a function joint opening and subsequently of joint spacing and temperature range from PCC placement to minimum temperature. Adhesive failures can be either partial-depth adhesive-loss or full-depth adhesive loss.

A method for joint seal design with survival criteria is suggested in Lee et al. [2003]. The observations of joints in LTPP seasonal monitoring program (SMP) sites led to the consideration that variability of joint openings in pavement sections and erratic large openings at a considerable portion of joints may be related with adhesion-type failure. In this model, joint openings are estimated based on the Lee-Stoffels model which is a probabilistic model that can predict the magnitude of joint opening with its probabilities. If the joint openings for any given circumstances could be known before hand, it would help in choosing a sealant with the appropriate maximum permissible elongation properties. The sealant must have the required elasticity to be able to return to its original shape after the elongation. This procedure accounts for freezing and joint cracking and is as follows:

1. Estimation of the probability of joint freezing (P_{jf})

$$P_{jf} = e^{(4.332 - 2.645 \,.\, \text{Pavement Type} - 16.565 \,.\, \text{Res D/PCC T})} / [1 + e^{(4.332 - 2.645 \,.\, \text{Pavement Type} - 16.565 \,.\, \text{Res D/PCC T})}$$

- Where: Pavement Type = 0 for JPCP; 1 for JRCP

  PCC T = PCC thickness (inches)

  Res D = reservoir depth (inches)

2. Estimation of probability of transverse cracking

   Use of established fatigue crack models suggested.

3. Estimation of probability for a pair of integrated slab length (ISL's) for a given joint

   Moving joints: $P_{(ISL\_Left,ISL\_Right)} = (1 - P_{jf})*P_{(ISL\_Left)}*P_{(ISL\_Right)}$

   Freezing joints: $P(0,0) = P_{jf}$

4. Computation of the maximum slab movement for ISL's

Probability of Given ISL for given Joint

ISL	Probability
0.5 JS	P_{crack}
1 JS	$(1 - P_{crack}).(1 - P_{jf})$
1.5 JS	$(1 - P_{crack}).P_{jf}.(P_{crack})$
2 JS	$(1 - P_{crack}).P_{jf}.(1 - P_{crack}).(1 - P_{jf})$
2.5 JS	$(1 - P_{crack}).P_{jf}.(1 - P_{crack}).P_{jf}. P_{crack}$

Adhesive failures will also occur when conditions are not favorable for the sealant to bond to the joint reservoir walls.

4.4 Analysis of Cohesive Failures

Cohesion is the ability of the sealant to resist tearing from tensile stresses. Cohesive failures result from the changes in internal stresses of a sealant while being stretched and compressed over a range of temperatures. These changes in internal stresses are called the sealant's modulus. For a sealant to be able to resist cohesive failures, low modulus is desirable. Low modulus sealants are especially important in cold weather climates. This is because in cold weather the concrete pavement contracts. As the pavement sections contract the joints are pulled apart, thus opening up the joint. As the joint opens, it stretches the sealant that is adhered to the faces of the joint walls. This stretching creates internal stresses in the sealant. If these stresses exceed the permissible elongation of the sealant, the sealant tears or breaks. This is called cohesive failure of the sealant. Cohesive failures can be either partial-depth failures or full-depth failures.

As explained earlier, depth of the joint sealant has considerable effect on the stresses and strains applied to the sealant due to the joint movement. A deep joint leads to high stresses while a shallow joint leads to lower stresses. Cohesive failures are thus related also related to joint movement and the configuration of the joint. The higher stresses and strains resulting from deep joints are more likely to cause the sealant to break or tear. It appears therefore that cohesive failures are a function of the shape factor. Data from LTPP sites also confirm that these failures are more frequent when the width to depth ratio is either too large or too small. Materials with low modulus properties are less likely to fail in cohesion and therefore more preferable as sealing materials. Available data indicate that most sealing materials fail more in adhesion rather than in cohesion, especially in areas that experience cold weather. This may be due to the fact that the pavement experiences the greatest opening of joints during the cold weather period when the sealant material will be colder and more rigid. As the joint opens, the now more rigid sealant does not stretch equally with this movement and so separates from the joint walls as the open up. Once adhesion to the joint reservoir is lost, there is no more stretching of the sealant to create the internal build-up of stresses that will cause cohesive failure.

4.5 Compatibility

This is measured by the relative reaction of a sealant to materials it comes into contact with. Compatibly appears to be a function of the chemical composition of the sealant. Apart from silicone sealant, there appears to be no observation or documentation of any of the other sealants to the pavement material. Instances of silicone reacting with concrete pavements containing limestone aggregates have been reported in Virginia, Michigan, and Iowa [Morian et al. 1998]. Khuri [1998] observed in Virginia that priming reduced this reactivity. It appears that the primer acts as a barrier between the sealant and the limestone aggregate.

4.6 Weatherability

Weatherability is the ability of the sealant to resist deterioration when exposed to elements such as ultraviolet sun rays and ozone. Like compatibility this property appears to be a function of the composition of the sealant. PVC coal tar and asphaltic sealants have been recorded to react with the elements. PVC coal tar has the worst oxidation rate. These sealants lose their flexibility when oxidized with the level oxidation increasing with age. Hot weather appears to accelerate oxidation with LTPP data indicating that the worst levels of oxidation are recorded during the summer months. It has been observed that overbanding these sealants help reduce the rate of oxidation. This may be due to the fact that when overbanded, the action of tires rubbing the surface of the sealant slows down the oxidation process.

4.7 Debris/Incompressibles Intrusion

When the sealant fails to adhere to the reservoir wall, or breaks in cohesion, incompressibles are able to enter the joint system. During cold weather when the concrete pavement contracts and the joints open up, these incompressibles/debris collect and build up at the bottom of the joint. As the weather gets warmer and temperatures increase the concrete pavement expands, closing up the joints. The incompressibles that have entered the joint cannot compress as the joint forces to close up with the concrete expansion. This leads to stresses being created at the bottom of the concrete pavement slab. As stresses increase, failure of the concrete occurs. As the pavement slab warps, diagonal tension is created in the slab causing conical spalling. Repetitive annual cycles of this nature can consequently lead to blowup and faulting of the slab at the joint. Debris intrusion thus appears to be a function of sealing as it is often the failure of the sealant that results in debris intrusion. It can also be inferred that sealant survival is thus directly related to conical spalling and thus pavement faulting and blowup. It appears that all the major failure types and causes of pavement distresses are directly or indirectly related to joint opening and closing. Thus joint spacing also has a part to play in effective sealing since longer joint spacing will lead to higher rates of expansion and contraction and thus more stress buildup.

4.8 Qualitative Analysis of SHRP-H-355 Test Sections

4.8.1 Overview

Comparison of the performance of materials in each joint sealant configuration after 18 months indicates that though differences exist in the amount of failure between materials, there is little statistical difference in spall and adhesion failure. Exceptions to this are that Mobay 960-SL and Koch 9005 developed less full-depth spalls than Crafco 221 in configuration 1 (sawed and recessed) in the dry non-freeze area. Koch 9005 was showing better performance than SOF-Seal in configuration 2 (sawed and overband) and configuration 4 (sawed and flush-filled) in the dry freeze zone. Mobay

960-SL had more full-depth spalling than the other materials in configuration 1 in Iowa (wet freeze). All materials were experiencing less spalling than Dow Corning 888 in configuration 1 in Kentucky (wet freeze).

At the dry non-freeze test site, Crafco 231 was having more adhesion loss in configuration 1 than the other materials. Crafco 221 and Crafco 231 were performing better than Koch 9005 and Meadows Hi-Spec in configuration 4 in this same zone. Koch 9050 polysulfide and Koch 9030 were developing more adhesion loss in configuration 1 in the dry freeze zone than other sealants. Crafco 231 and Koch 9005 were performing better than Koch 9030 in configuration 2. In the wet freeze zone (Iowa), Meadows Sof-Seal was not performing as well in adhesion as the other sealants in configuration 1, and Koch 9030 was not performing as well as the others in configuration 3 (plow and overband). In the wet non-freeze zone full-depth adhesion performance in configuration 3 was significantly different between materials. Performance decreased from Crafco 231 to Meadows Sof-Seal, then Koch 9005 and finally to Koch 9030 in that order.

At 18 months, full-depth spall failure remained at less than 3.2 percent of overall joint length for any of the materials, and remained at less than 2 percent of the joint length for 93 percent of all test sections. Full-depth adhesion loss was less than 1 percent for 71 percent of the material-configuration combinations. It was less than 2 percent for 83 percent of combinations, and less than 5 percent for 93 percent of combinations. The large amount of adhesion failure for Mobay 960-SL in Iowa (wet freeze) resulted from partial-depth spalls that loosened the sealant and pulled the sealant away from the remaining joint wall over time. The large amount of full-depth spalling in

Mobay 960-SL and Dow Corning 888 at Kentucky (wet freeze) resulted from deteriorated concrete in one joint of each material.

Comparing the non-failure distresses, there was significant differences in performance between materials and configurations for partial-depth spalling and adhesion loss than for full-depth spalling and adhesion loss. Crafco 231 developed less partial-depth adhesion loss at the dry non-freeze site than Crafco 221, Koch 9005, and Meadows Hi-Spec in configuration 1. Also the silicone sealants developed less partial-depth adhesion loss than the rubberized asphalt sealants. The silicone sealants and Crafco 231 showed less partial-depth adhesion loss than the remaining rubberized asphalt sealants in configuration 1 at the dry freeze, wet non-freeze and one wet freeze (Iowa) sites. At the dry freeze site, Crafco 231 and Koch 9005 in configuration 2 experienced less partial-depth adhesion loss than Koch 9030 or Meadows Sof-Seal. Crafco 231 and Meadows Sof-Seal developed less adhesion loss in configuration 4 at the dry freeze site than Koch 9005 and Koch 9030.

With regard to partial-depth spalling, only one wet freeze zone (Iowa) and the dry freeze zone (Colorado) showed significant differences in partial-depth spalling between materials in each configuration. The silicone materials in the dry zone developed more partial-depth spalls in configuration 1 than most of the other hot-applied sealants. At the wet freeze sites in Iowa, there was no significant difference in spall development between silicone and the hot-applied sealants.

Joints primed and sealed with non-self-leveling Dow Corning 888 silicone sealant showed more partial depth spalls than unprimed joints. Joints primed and sealed with self leveling Dow Corning 888 silicone sealant however did not show significant difference in partial-depth spall development from unprimed joints with the same material.

It appears from the above that most hot-applied sealants installed developed less partial-depth adhesion loss when installed with configurations 2, 3, and 4 i.e. sawed and overband, plowed and overband, and sawed and flush-filled than when installed in configuration 1 (sawed and recessed). Crafco 231 appears to be the exception to this as it developed no significant difference in partial-depth adhesion loss in four of the five test sites. The larger amount of spalling appearing in the silicone sealants may be partly due to the stress developed when the sealant is elongated. Stress in silicone sealants are generally much higher than in rubberized asphalt sealants when stretched to 150 percent of their original length. This fact was confirmed by laboratory tests carried out. The laboratory tests also indicated that the bond strength between the sealant and the concrete was better than the tensile strength of the concrete, and in conjunction with cold weather elongation and traffic loads more new spalls developed along the joints containing silicone sealants.

4.8.2 Sealant Performance as Related to Position along Joint

Results of the study of the effect of tire contact and traffic loads, spall and adhesion failure indicate that spalling occurs more frequently in the wheel paths. However, only negligible differences in adhesion as a function of distance from the shoulder edge had been observed at as at 18 months. These differences do not also correlate well with the wheel path positions. These relations are indicated in Figures 5 and 6 in Appendix 2. A relationship does exist between spalling and the distance from the shoulder edge. At the wet freeze Iowa site and the dry freeze zone (Colorado), the partial depth spalling is higher at the wheel path positions. The dry non-freeze, wet freeze in Kentucky, and the wet non-freeze sites did not contain enough spalls to indicate any significant difference in spalling intensity in the wheel path.

4.8.3 Comparison of Sealant Performance between States

Figures 7 and 8 in Appendix 2 compare partial-depth and full-depth adhesion loss between states. The silicone sealants appear to have excellent adhesion performance in all states and therefore climatic regions. Majority of the slight adhesion loss in silicone sealants indicated are related to partial-depth spalling. A few occurrences of full-depth adhesion failure were observed in the hot-applied seals. Most sealants indicated less than 0.5 percent of the joint length failed. For three of the four hot-applied sealants used in the dry freeze sites and the wet freeze sites in Kentucky, partial depth adhesion loss is larger. In the wet non-freeze sites full-depth adhesion failure was more prevalent. This was mostly due to the seal performance in configuration 3 where silicone sealant on the plowed joint face did not allow good adhesion.

Partial-depth and full-depth spall failure as shown in Figures 9 and 10 in Appendix 2 are more prevalent at the dry freeze (Colorado) and wet freeze (Iowa) sites. Joints in these cold climatic regions experience large opening at the time the sealant materials are colder and stiffer. Spalling at the Iowa sites was greater than at the Colorado sites and may possibly be due to differences in aggregate and mortar strength or differences in the amount of moisture present.

4.8.4 Comparison of Sealant Performance over Time

Micro- and macro-thermal cycling come into play as the time a joint sealant remains in position increases. This causes widening and closing of the joint reservoir as well as softening and hardening of the sealant. Weathering and the effects of oxidation and ultraviolet light makes the sealant harden. Traffic loads accumulate shear stress cycles for the sealant and the surrounding concrete and also reduce sealant overband thickness. The ability of the sealant materials to resist the cumulative effects of time is a key property that will help rank sealant performance. This performance comparison classifies the sealants into two types in this study: silicone and hot-applied. The effects of time on adhesion and spall failure are presented in Figures 11, 12 and 13 in Appendix 2.

The relationship of time after installation with average full-depth adhesion loss for all the test sites is indicated in Figure 11 for hot-applied sealants. The trend appears to indicate increased adhesion loss with time. At the South Carolina (wet non-freeze) site there was an increase in adhesion loss in the eighth and ninth months after installation immediately following the first winter. Very little adhesion loss occurred in the silicone sealants over the 18 month study period.

The relationship between time and spall failure at the test sites is indicated in Figure 12 for silicone sealants and Figure 13 for hot-applied sealants. Both figures indicate a large increase in spalling in the fall and early winter period between the fifth and the ninth months at the dry freeze site in Colorado and the wet-freeze site in Iowa. The wet freeze site in Kentucky also indicated a slight increase in spalling through the early winter period. Spalling in the first year after resealing joints in the two cold region states was significantly increased through the early winter months.

4.8.5 Key Findings

After 82 months of this study, a significant amount of overall seal failure had occurred at all five sites. At that stage about 52 percent of treatments were exhibiting a minimum of 25 percent failure, predominant distresses being adhesion loss and spall failure. In addition to the evaluation of overall seal performance, a service-life comparison was performed. A 75-percent overall effectiveness level for each joint was selected to define failure. A joint with an overall effectiveness greater than or equal to 75 percent was classified as surviving. A joint with an overall effectiveness of less than 75 percent was classified as failing. Nearly 50 percent of the joints had reached the 75 percent effectiveness level at the time of the last evaluation, thus allowing interpolation of the service life. All remaining joint performance service lives were extrapolated, limited by a maximum allowable time of 200 months. Table 4.1 presents the service life, or the time to 75- percent effectiveness for the materials used.

Table 4.1 Projected Service Life in Months for Tested Joint Sealants [FHWA 137 1999]

Sealant Material	Time at Which 75% Effectiveness Level Was Reached in Months						
	Configu-ration[1]	Arizona ADT=10K[2]	Colorado ADT=27K	Iowa ADT=19K	Kentucky ADT=14K	South Carolina ADT=19K	Ave-rage
Koch 9005	1	116	66	94	156	63	99
	2	112	66	91	191	90	110
	3	-	-	148	182	49	126
	4	105	61	-	-	-	83
Crafco RS 231	1	52	80	76	86	92	77
	2	135	69	118	108	138	114
	3	-	-	103	155	80	113
	4	83	72	-	-	-	78
Meadows Sof-Seal	1	-	34	40	39	55	42
	2	-	40	51	64	46	50
	3	-	-	57	161	31	83
	4	-	43	-	-	-	43
Koch 9030	1	-	31	50	60	41	46
	2	-	32	63	50	41	51
	3	-	-	59	143	15	72
	4	-	37	-	-	-	37
Meadows Hi-Spec	1	43	-	-	-	-	43
	2	94	-	-	-	-	94
	4	76	-	-	-	-	76
Crafco RS 221	1	65	-	-	-	-	65
	2	105	-	-	-	-	105
	4	117	-	-	-	-	117
Dow 888	1	198	145	130	186	178	167
Dow 888-SL	1	183	110	125	164	186	154
Mobay 960-SL	1	194	93	65	115	168	127

1 - The four installation configurations used were:

Method 1 = Joint faces resawed and sealant recessed. Method 2 = Joint faces resawed and sealant overbanded. Method 3 = Joint faces plowed and sealant overbanded.

Method 4 = Joint faces resawed and sealant flush-filled

2 - Two-way average daily traffic (ADT), vehicles per day

4.9 Analysis of Questionnaire Responses

4.9.1 Wet Freeze Region

The questionnaire used for this study is presented in Appendix 1. Ten states lying within the wet-freeze region responded to the questionnaire. Eighty percent of these states have used and continue to use sealants in their concrete pavement joints. The exceptions to these are Wisconsin and Vermont. Wisconsin as a result of the studies presented in chapter 3, has discontinued all forms of sealing since 1997. According to the response received, Vermont currently has no concrete pavements as all their old concrete pavements have long since been overlaid with asphalt. Out of the states which practice joint sealing, 62.5 percent have sealed concrete pavement joints for twenty years or more but less than thirty years, and the remaining 37.5 percent have sealed their joints for thirty years or more.

Eighty-seven percent of the states that do seal use all the three most common types of sealant, namely asphaltic, silicone and neoprene in varying degrees. 12.5 percent of the states that seal have their sealed pavements on high traffic volume roads only. Fifty percent have sealed pavements located on medium and high volume roads. Twelve point five percent have sealed pavements located on medium traffic volume roads only, and the remaining 25 percent have sealed pavements located on low, medium and high traffic volume roads.

Seventy-five percent of respondents indicated that the performance of one or more of the sealants justify the sealant use and contribute to an increase in pavement life. Twelve point five percent of sealant users indicated inability to ascertain whether sealant performance justifies its use and contributes to pavement life. The remaining 12.5 percent indicated that sealant performance does not justify its use. Iowa and Kentucky indicate that the best performing sealants for these states are the hot-pour sealants. Iowa indicated that silicone sealants perform no better than the hot-pour sealants in that state, therefore not justifying the use of silicone which is 8 to 10 times more expensive. In Kentucky however, silicone sealants are rank number 2 after hot-pour on the preference scale.

The apparent difference in silicone sealant performance for these two states, both of which lie in the wet-freeze zone may be due to differences in temperature, Iowa having colder tempeaures than Kentucky. If this is so, then it may be inferred that the silicone sealant appears to perform relatively better under slightly warmer conditions.

The cost and performance of silicone, rubberized asphalt and hot asphalt justify their use in Virginia while the cost and performance of neoprene does not justify its use in this state. Silicone sealant is the most preferred sealant in Virginia where rubberized asphalt is only used for the maintenance of existing transverse joints.

New York state has used silicone extensively until recently when the state commenced experimenting with ASTM D 3405 (rubberized asphalt). These experimental sites are still being monitored and no conclusive information has been made available yet.

The latter two responses also go to reinforce the assertion that silicone sealant appears to perform better in the warmer areas of the wet-freeze zone.

4.9.2 Dry Freeze Region

Only Colorado and Oregon responded in this group. Since Oregon has very little jointed concrete pavement, no pertinent data was available. Colorado has used Dow 888-SL silicone sealant for 15 years on low, medium and high volume traffic roads. Experience indicates that self-leveling silicone does not appear to work well in Colorado where air bubbles push through the sealant before it sets creating voids. Non-self-leveling silicone sealants appear to work better with a closed cell backer rod. In Colorado, experience has shown that the joint seals work best with a width to depth ratio of 1:1. It is also indicated that the narrower the joint the better the sealant appears to perform.

4.9.3 Wet Non-Freeze Region

Only one response was received for this region from Mississippi. This state has used low modulus silicone sealants on high volume traffic roads for 20 years but did not comment on the performance.

4.9.4 Observations from Responses

It appears from the responses received that most states consider it beneficial to seal their concrete pavement joints with one form of sealant or other. For the sealed joints to be truly beneficial it appears a rigid regime of regular inspection and maintenance must be observed. Installation procedures and construction methods and practices must be monitored strictly for the sealants to perform creditably. Unfortunately, although the majority of states consider sealing beneficial to pavement life, there appears to be no data to assess quantitatively the measure of both physical performance and cost effectiveness. Another vital observation from the responses is that silicone sealant appears to perform better in the warmer areas of the wet-freeze zone than in the colder parts.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Summary

This study indicates that on the whole sealing of the joints in jointed concrete pavements is necessary to improve the performance of these pavements. The joint sealants minimize the rate of deterioration of the pavements by limiting the amount of water infiltration into the joints. Sealants also prevent incompressible materials from entering the joints. The main factors influencing the performance of the sealants are joint movement, sealant reservoir shape, bond between sealant and side wall, the properties of the sealant, voids under the joint, and workmanship/inspection. The sealant must have good adhesive and cohesive properties, and must be able to accommodate expansion and contraction of the pavement without sustaining damage. It must also have good weathering properties. In addition to following, the manufacturer's instructions, strict installation procedures and good construction practices must be observed to ensure that the sealant adheres to the sides of the joint reservoir and performs its function within a reasonable life cycle.

The following are six main steps that previous studies have established as the steps in the design and construction of sealed transverse joints in jointed Portland cement concrete pavement:

I. Selecting a sealant material that is appropriate for the given conditions

II. Estimating the joint movements

III. Designing the sealant reservoir

IV. Primary sawcutting to create the joint

V. Secondary sawcutting to create the joint sealant reservoir

VI. Installing the sealant

It appears in this study that a good estimation of the joint movement is essential in the selection of an appropriate sealant and must therefore be the first step.

Available sealant materials can be classified into three main groups:

1. Thermoplastic material which can be in turn sub grouped into cold-applied and hot-applied. The hot applied sealants include asphalt cement, rubberized asphalt cement, polymerized asphalt cement and PVC coal tar. Cold-applied sealants include cutback asphalt and asphalt emulsion.
2. Thermosetting materials which can be either one-component or two- component. These include silicones, polysulfides, and polyurethanes of which the most commonly used is silicone. These types of sealants often require the use of a primer or bonding agent. Silicone sealants can be broadly classified as self-leveling and non self- leveling. The non self-leveling silicone materials require a hand-tooled finish.
3. Compression seal materials are premolded strips of styrene, urethane, neoprene or other synthetic materials. These are inserted into the joint in a state of compression and do not therefore rely on adhesion for bonding. Compression seal materials are designed to always remain in a compressed state ranging between 20 to 60 percent. Their design and installation must be such that they

always remain in a compressed state at both maximum and minimum joint-opening width. Compression seals also typically require the use of a primer or bonding agent for installation. The lubricating effect of a primer is necessary for installation because the seal is larger than the sealant reservoir into which it is installed. One problem identified with compression seals is the development of compression set in the seal. This problem relates to the fact that the acceptance test, ASTM D2628, requires 83 to 88 percent rebound, but only for a single cycle. This testing does not preclude compression set of the seal material. Other problems are related to poor construction quality control. Overcutting the depth of the sealant reservoir is an additional problem. Results of the case studies indicate that since the stringent quality control required during construction for good performance of compression seals is difficult to meet in practice, their cost seldom justifies their use.

Also notable among the findings of this study are the following:

1. Adhesive failures appear to be a function of temperature, with low temperatures causing more adhesive failure.
2. Cohesive failures appear to be a function of the shape factor i.e. width to depth ratio. These failures are more frequent when the width to depth ratio is either too large or too small.
3. Weathering of PVC-coal tar and rubberized asphalt sealants appears to be a function of age as well as hot weather. These sealants appear to suffer more weathering damage during the summer months.

4. The service lives of the PVC-coal tar and rubberized asphalt appear to be less than ten years. It is thus more cost effective to use these for the maintenance of pavements that are projected to be overlaid a maximum of six years.

5.2 Recommendations

Short-term studies cannot provide conclusive results of sealant performance. It is important therefore that further long term studies continue as with the SHRP programs. In the interim, the following recommendations for choosing the best sealing system will tentatively be proposed from this study:

1. For new pavements shorter joint spacing must be chosen at the design stage to minimize slab movement.
2. Where feasible, granular or stabilized subbase material should be selected.
3. A good estimation of the expected joint movement must then be done.
4. After the maximum movement has been determined, the sealant type can be selected based on the expected movement.
   a. The maximum allowable elongation of the selected sealant must be at least equal to the maximum expected movement.
   b. For cold regions with higher joint movement, a low-modulus sealant must be chosen.
   c. Low-modulus rubberized asphalt sealants appear to have greater working range with respect to low temperature extensibility and resistance to high temperature softening and so would be suitable for areas with hot summers and cold winters.

5. The joint configuration must then be designed based on the selected sealant.

   a. For hot-applied sealants to perform properly, a sealant reservoir shape factor of 1:1 must be maintained. It appears that this shape factor provides the minimum relationship between the reservoir width and depth to achieve the required adhesion performance characteristics of this type of sealant. The use of a backer rod to ensure the proper shape factor appears critical to the performance of hot-poured sealing materials. It is recommended that a closed cell backer rod be used in deep joints as this keeps the joints from becoming too strong so as to defeat its own purpose. The backer rod prevents the sealant from bonding to the bottom of the reservoir. In addition, closed cell foam does not hold water, thereby eliminating a host of other problems.

   b. For silicone sealant materials, a width to depth ratio of 2:1 appears to be good. The use of a backer rod ensures that proper dimensions are obtained and is thus recommended. It appears from previous studies that silicone sealants are not compatible with pavements that contain limestone aggregates.

6. In regions with frequent snow plowing activity, it is best to use a recessed joint configuration rather than overband or flush-filled. This will prevent the sealant from being pulled out of the reservoir by the snow plows.

This selection procedure is presented in a systematic flow chart for easy reference and use in Figure 14.

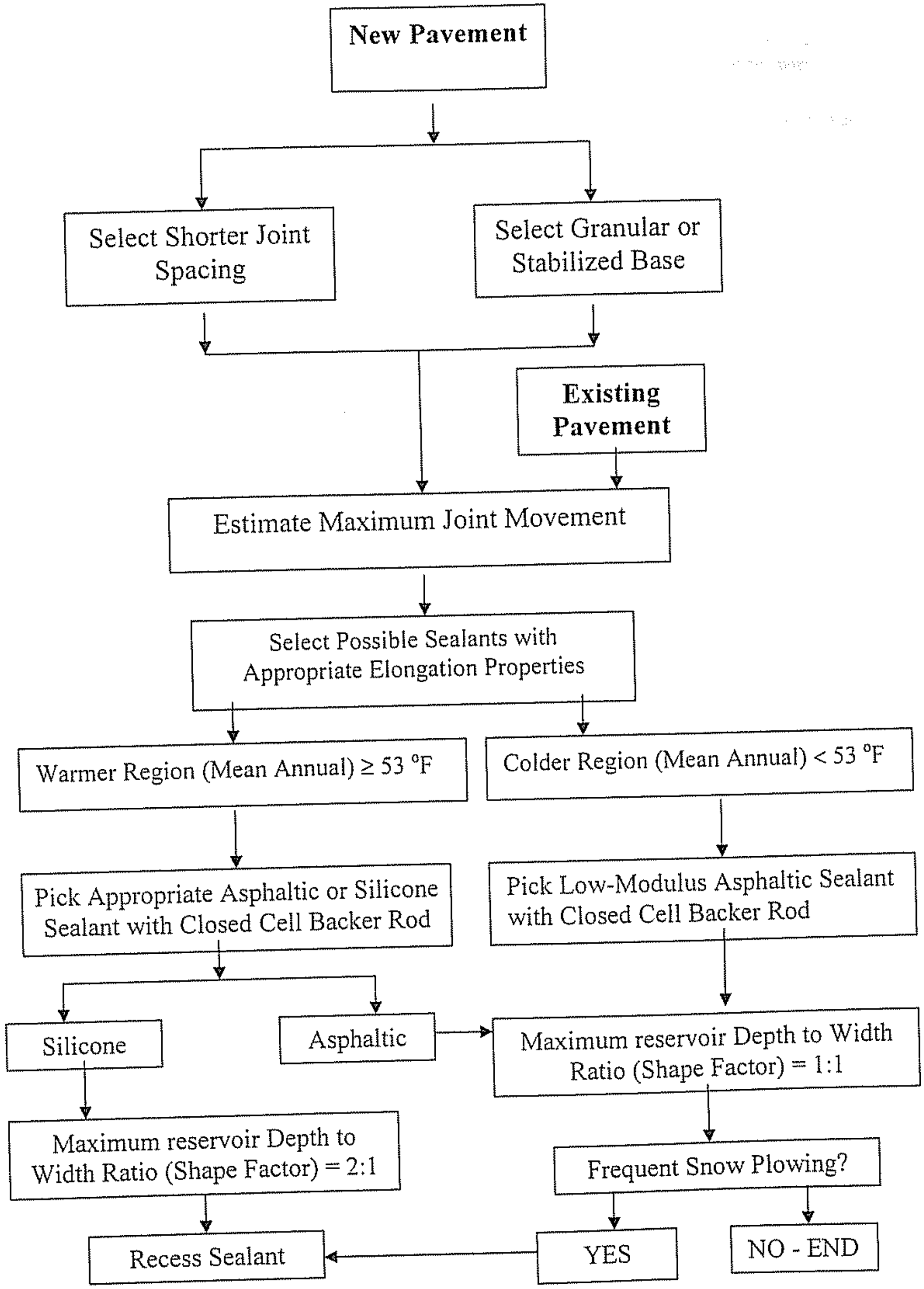


Figure 14 Flow Diagram for Sealant System Selection

5.3 Future Research

Areas for future research towards better joint seal performance are:

1. Detailed investigation of factors affecting the strength of the bond between the sealant and the joint reservoir walls is needed.
2. Long range (15 to 20 years) field studies of the performance of the commonly used sealants needs to be carried out for each state with PCC pavements to enable the development of performance-based specifications.
3. Research into the feasibility of the development of testing procedures to verify sealant performance in the field is needed to eliminate the current subjective visual assessments.

APPENDIX 1

SAMPLE OF QUESTIONNAIRE

SEALING OF CONCRETE PAVEMENT JOINTS

1. State____

2. For how long has concrete pavement joint sealants been used in your state?

   _____20 years _____15 years _____10 years _____5 years

3. Type of sealant materials used?

   Sealant name______________________ Cost per unit length________

   Sealant name______________________ Cost per unit length________

   Sealant name______________________ Cost per unit length________

   Sealant name______________________ Cost per unit length________

4. Truck traffic on the sealed joint concrete pavement is:

   __________High __________ Medium __________ Low

5. Has the sealant contributed to extending the life of the pavement?

   ________ Yes ________ No

6. Does the cost and performance of the sealant justify its usage?

   Sealant name______________________ Yes No

   Sealant name______________________ Yes No

   Sealant name______________________ Yes No

   Sealant name______________________ Yes No

7. Please provide any comments/observations you may have on the use of sealants in concrete pavement joints.

____

____

____

____

APPENDIX 2

Table A2.1: Sealant Names and Abbreviations [Evans and Romine 1993]

Sealant Name	Sealant Type	Abbreviation
Crafco Roadsaver 221	Rubberized Asphalt	C-221
Crafco Roadsaver 231	Low Modulus Rubberized Asphalt	C-231
Koch 9005	Rubberized Asphalt	K-9005
Koch 9030	Low Modulus Rubberized Asphalt	K-9030
Meadows Hi-Spec	Rubberized Asphalt	M-HS
Meadows Sof-Seal	Low Modulus Rubberized Asphalt	M-SS
Dow 888	Silicone	888
Dow 888-SL	Self-Leveling Silicone	888-SL
Mobay 960-SL	Self-Leveling Silicone	960-SL
Mobay 960	Silicone	960
Crafco Roadsaver 903-SL	Self-Leveling Silicone	RS-SL
Koch 9050	1-Part Polysulfide	K-9050

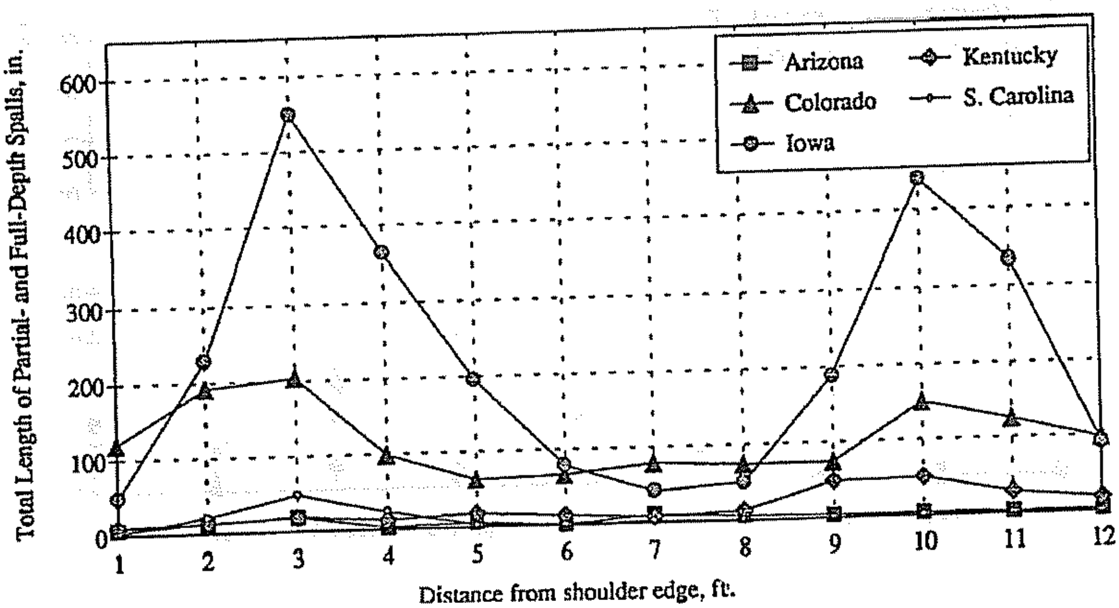


Figure 5 New Partial-Depth and Full-Depth Spalls versus Distance from Shoulder [Evans et al. 1993]

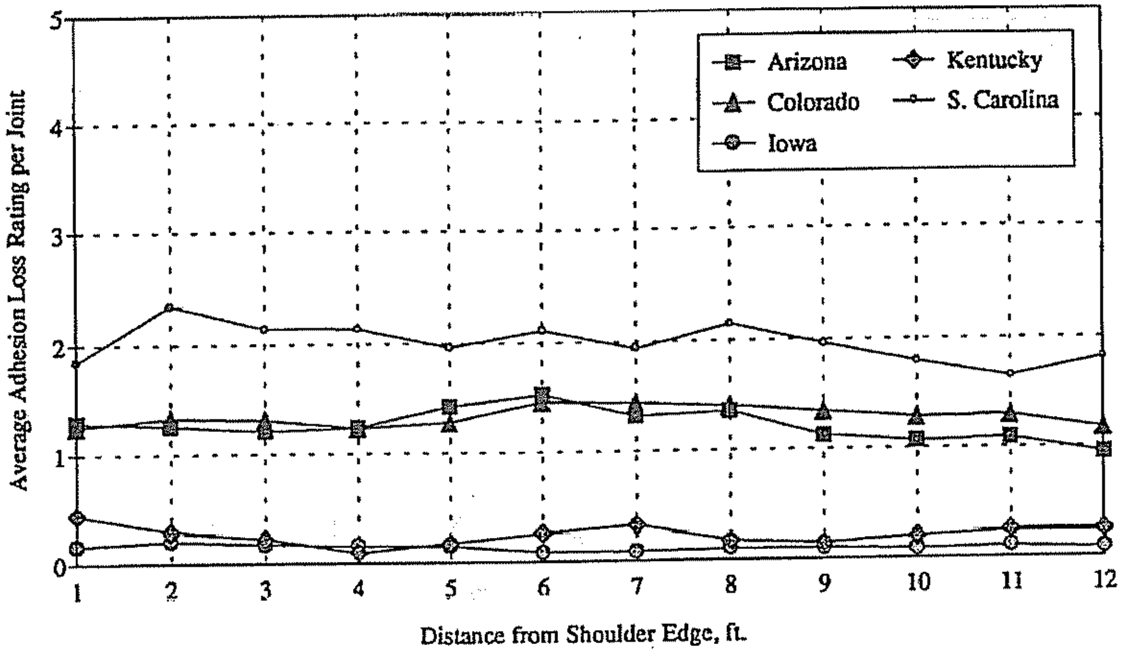


Figure 6 Adhesion Loss Rating versus Distance from Shoulder at 18 Months [Evans et al. 1993]

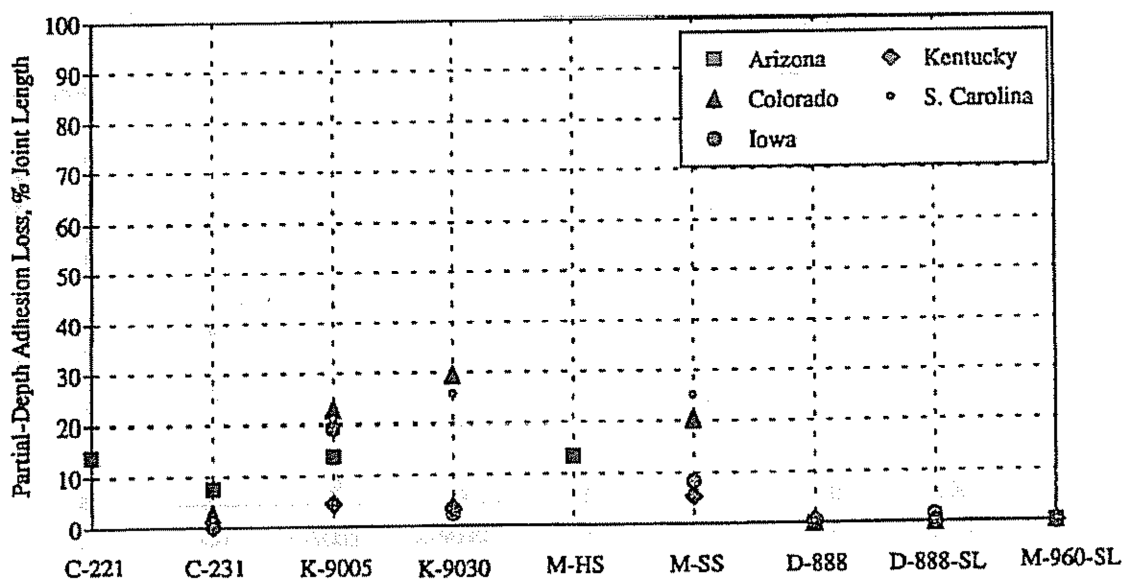


Figure 7 Partial-Depth Adhesion Loss for Recessed Joint Seals at 18 Months [Evans et al. 1993]

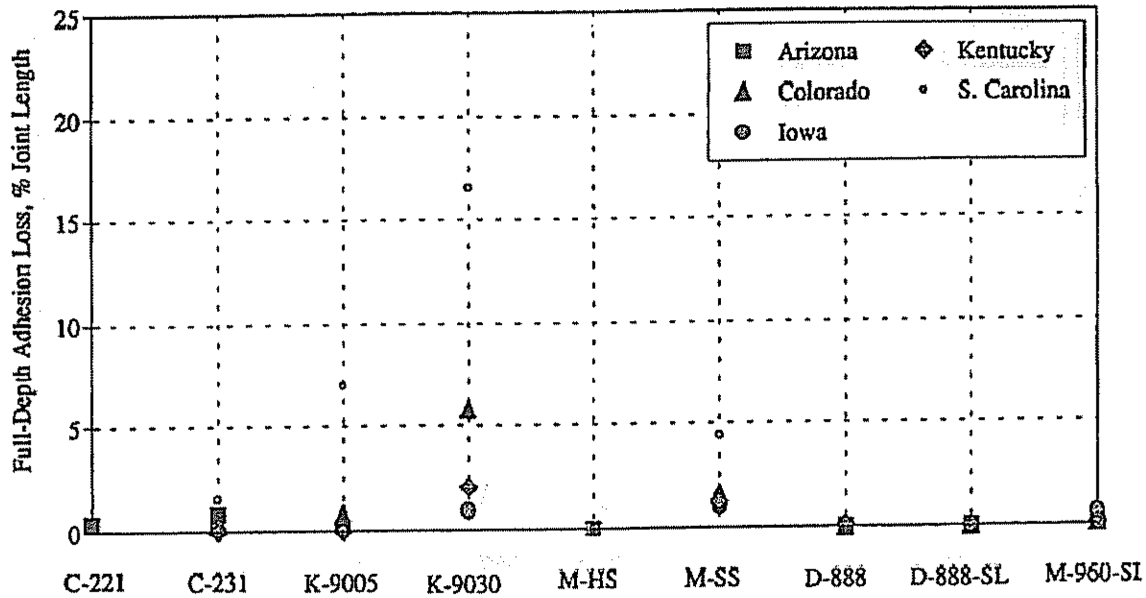


Figure 8 Full-Depth Adhesion Loss for Recessed Joint Seals at 18 Months [Evans L. D. et al. 1993]

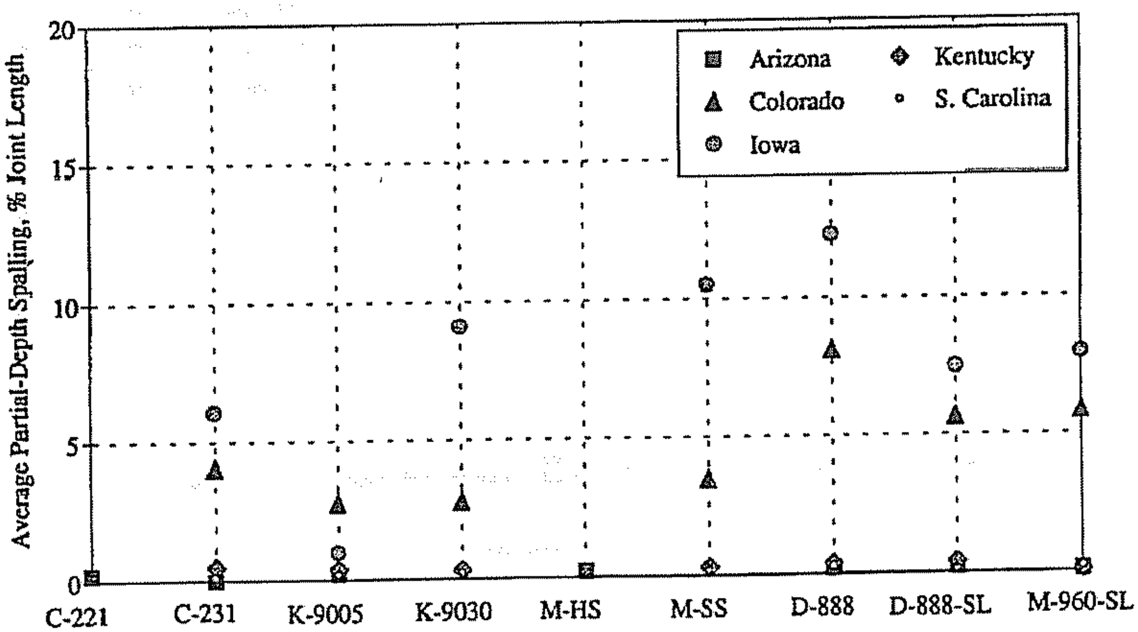


Figure 9 New Partial-Depth Spalls for Recessed Joints at 18 Months [Evans L. D. et al. 1993]

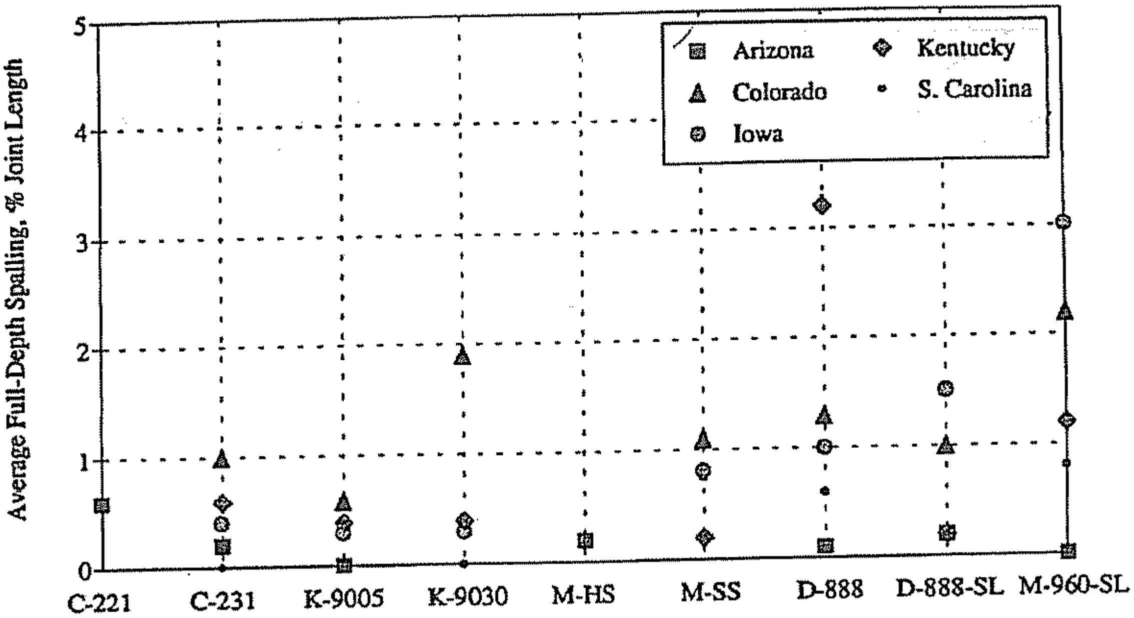


Figure 10 New Full-Depth Spalls for Recessed Joints at 18 Months [Evans et al. 1993]

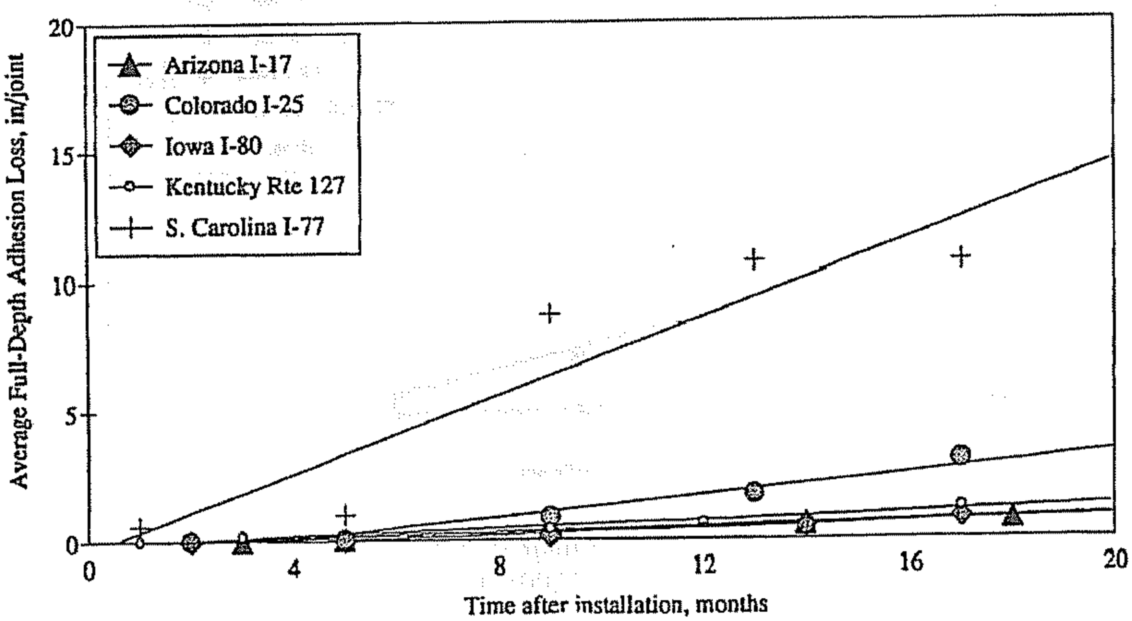


Figure 11 Relation of Time to Adhesion Loss for Hot-Applied Sealants [Evans et al. 1993]

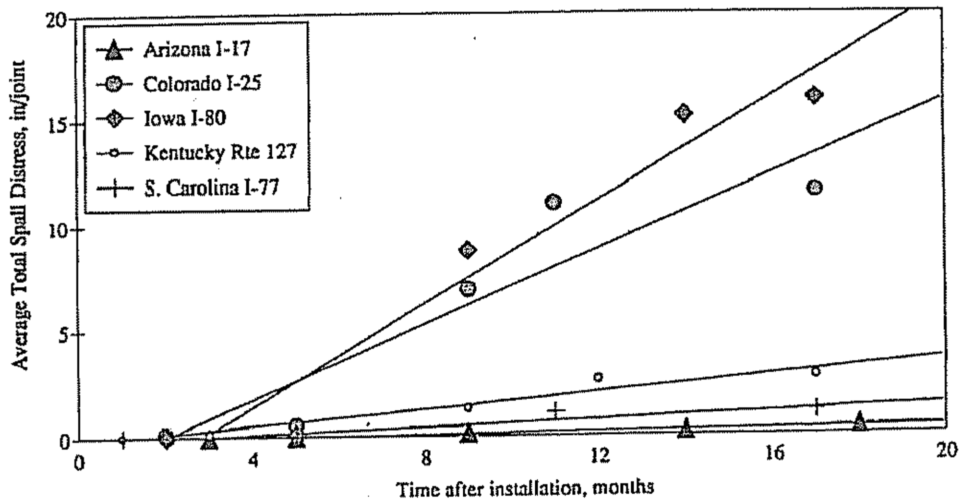


Figure 12 Relation of Time to Spall Failure for Silicone Sealants at 18 months [Evans et al. 1993]

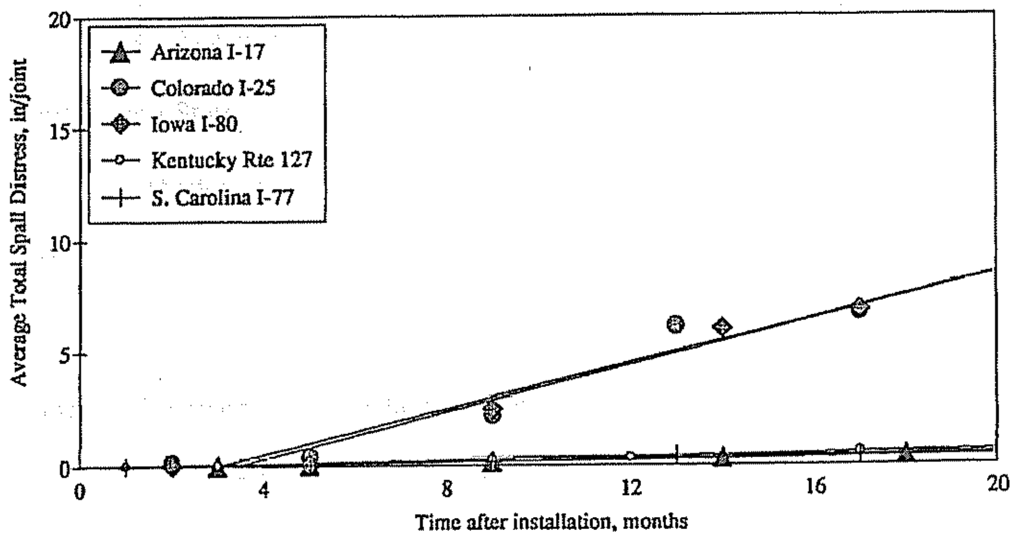


Figure 12: Relation of Time to Spall Failure for Rubberized Asphalt Sealants at Eighteen months [Evans et al. 1993]

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