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(As of December 31, 1963)

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Foreword

The eight papers presented here are an attempt to illustrate and summarize some of the thoughts and research in the area of joint sealants for highways and bridges. The scope is rather broad and the language in most papers is not very technical; therefore, they may be of interest to many who are concerned with joint sealing materials, methods and problems.

Westall reviews present methods of joint forming in portland cement concrete and in a way defines "the gap to be spanned by the sealant."

Two papers by Cook deal with research on poured-in-place sealants, illustrating some of the properties of the material and effect of geometry on stresses and strains.

Tons reviews briefly the various types of joints to be sealed and emphasizes that bridging a gap between two concrete slabs is like building a bridge across a river. Inasmuch as there are different types of bridges, depending on engineering considerations, there should be different types of sealants to serve under varied conditions.

Dreher and Watson discuss the mechanics, merits and problems with so-called compression seals, which are preformed and placed in a joint in a precompressed condition. One of the main hopes behind a compression seal is to avoid adhesion failures.

Graham discusses actual field tests and compares a certain compression seal with several other sealants. His preliminary conclusion is that under the conditions tested the compression seal shows promise of lasting longer than others.

Finally, Britton discusses the problems encountered in bridge joint sealing. Cook in one of his papers also puts emphasis on materials for bridge joints.

There are still many problems to be solved in the joint sealant area. However, considerable progress has been made with new materials and techniques. We also have arrived at a point where a development of a "preliminary numerical joint seal design method" for varied conditions is imminent. This has not been just a recent development; many ideas and developments stem back from this Committee's work under two past chairmen, namely William Van Breemen and C. C. Rhodes.

Contents

Methods of Forming Joints in Portland Cement Concrete Pavement

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The types of joints used in concrete pavement are (a) construction joints, both longitudinal and transverse; (b) expansion joints, full pavement depth with a compressible filler; (c) longitudinal center joints, sometimes called "hinge" joints; and (d) contraction joints, transverse across paving lanes. Although a large variety of joint types and devices have been tried by highway departments and the several airfield construction agencies, there are currently only four basic methods of forming joints in concrete pavement: (a) hand-forming, hand-tooling; (b) sawing joints; (c) forming in the plastic concrete by some type of insert left in the pavement; and (d) placing preformed joint filler ahead of the concrete to form expansion joints.

A historical background, tracing the development of current jointing practices, is provided. Types and purposes of joints used in concrete pavement are described and the four basic methods of forming joints are discussed in sufficient detail to provide a basis for evaluation of each method.

•PROVIDING JOINTS in concrete pavement has been a major construction problem since the necessity for joints was first recognized. Engineers, materials producers and others have conducted much research to attempt to develop the strongest, smoothest riding, most durable joints that it is practicable to provide. Although a large variety of joint types and devices have been tried by highway departments and the several airfield construction agencies, there are currently only four basic methods of forming joints in concrete pavement: (a) hand-forming, hand-tooling; (b) sawing; (c) forming in the plastic concrete by some type of insert which is left in the pavement; (d) placing formed joint filler ahead of the concrete to form expansion joints.

HISTORICAL BACKGROUND

For a better understanding of current practices, it may be useful to trace briefly the evolution of joints in concrete pavement in the United States. The first portland cement concrete pavement of which there is an authentic record was placed in Bellefontaine, Ohio, in 1892. This construction, as all early pavements, involved the slow and laborious processes of mixing and placing the concrete by hand. The pavement was constructed in small slabs or blocks, 5 or 6 ft square. Joints consisted of the spaces left between slabs and were full depth on the order of expansion joints. Tarred paper was placed between the blocks to allow for expansion.

Construction of small slabs or blocks appears to have been the pattern of concrete pavements built before 1900. The comparatively wide joints at such short intervals were subjected to damage by the steel-tired wheels of the animal-drawn vehicles of the era. A variety of metal devices were contrived to protect the slab edges from such damage. Since there was no particular requirement for smooth pavements, some of these devices seem to have served their purpose with considerable success.

Paper sponsored by Committee on Sealants and Fillers for Joints and Cracks in Pavements and presented at the 43rd Annual Meeting.

The decade from 1900 to 1910 was a period of much experimentation in joint spacing and design. Joint damage by steel-tired wheels was still a matter of much concern. In efforts to overcome this problem experienced with very small slabs, the designers of concrete pavement approached the other extreme by building large slabs with widely spaced joints. During this period all joints were expansion joints at full pavement depth. A few examples will illustrate the widely divergent practices of the time:

1. In Toronto, Canada, in 1902, concrete pavement was built of slabs 20 ft square with ¾-in. expansion joints between the slabs. The joints were filled with a material referred to as "paving pitch."
2. In Richmond, Indiana, in 1903, a concrete pavement was placed in "large" slabs with 1-in. wide expansion joints.
3. In Washington, D. C., in 1906, a pavement was built in slabs 100 ft long with 1-in. wide joints filled with a bituminous material.

Reports indicate that these and other pavements of large slab dimensions exhibited uncontrolled cracking between the joints.

By 1910, recognition of the automobile as a practical means of transportation began to stimulate road construction. A quotation from the July 9, 1913, issue of Engineering and Contracting is illustrative of the jointing practices of that time:

> Practice exhibits a heterogeneous array of expansion joint details, spacings and arrangements. This is most true of transverse joint practice. The plan is general of placing joints between pavement edge and curb and, when railway tracks occupy the streets, of placing joints on each side of the tracks just outside the tie ends. There is no similar uniformity in transverse expansion joint practice. They are spaced 25, 30, 37½, 50, 60 and 100 feet apart and the most common spacings are perhaps 25 and 30 feet. Usually they are square across the roadway but various diagonal arrangements are employed. Structurally the differences are wide. Joints with metal guard plates, joints with rounded edges only, joints of all widths from ¼ to 1 inch, joints with fillers of a dozen characters are employed.

It was perhaps the indifferent success of this wide variety of joint spacings that led to the construction of concrete pavements without joints except at locations where construction was stopped. By 1915, several states were building such pavements and the practice was continued in some areas even during the 1930's.

Until about 1919, all transverse joints in concrete pavements were expansion joints with spacings from about 25 to 100 ft. In 1919, at least one project was built with a type of weakened plane contraction joint for crack control. This was done by setting a thin board on edge on the subgrade and placing concrete around it. This practice appears to have been followed for a while. The irregularity of the crack on the slab surface, however, and the difficulty of effectively sealing it, soon led to the formation of a groove on top of the pavement for the contraction joint. About this same time, use was first made of longitudinal joints to control cracking.

Most of the changes leading to the types of joints currently used in concrete pavements occurred between 1920 and 1930. These changes were influenced or brought about by research projects such as the test road at Pittsburg, California, the Bates test road in Illinois and tests by the U. S. Bureau of Public Roads at Arlington, Virginia. Important factors in the changes were the primary engineering objectives of obtaining improved joint design and better pavement performance at lower costs. This led to rapid mechanization of concrete paving methods at the same time that assembly-line techniques were being applied to automobile manufacturing to reduce costs. During this period of mechanization, practical methods were developed for construction of joints in concrete pavements.

By 1930, the principles of joint design for concrete pavement were generally understood and the basic types of required joints were in use. There was a misconception, since corrected, regarding the use of expansion joints, as well as a lack of knowledge of the effects of joint dimensions on the performance of sealing materials.

TYPES OF JOINTS

Although the types of joints currently used in concrete pavement are generally well known, a brief review will perhaps help to prevent any misunderstanding of the following discussion of the methods of forming each type. The four types of joints (Fig. 1) used in concrete pavement are (a) construction joints, both longitudinal and transverse; (b) expansion joints which are full pavement depth with a compressible filler provided to permit the joint to close as the pavement expands; (c) longitudinal center joints, sometimes called "hinge joints," to relieve curling and warping stresses; (d) contraction joints in the transverse direction across paving lanes.

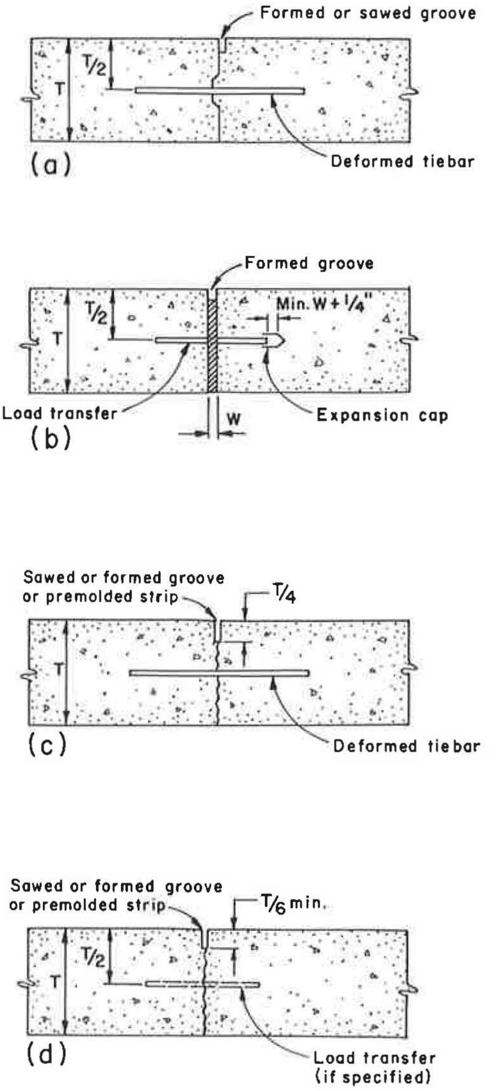

Figure 1. Basic types of concrete pavement joints: (a) construction joint, (b) expansion joint, (c) longitudinal center joint and (d) contraction joint.

Construction Joints

Construction joints are transverse header joints, installed wherever paving is interrupted, or longitudinal construction joints between lanes of multiple-lane pavement. Their purpose is to divide large pavement areas into convenient size for paving. Longitudinal construction joints are usually provided with deformed tie bars or tie bolts to prevent horizontal movement and with keyways or tongues and grooves built into slab edges to provide load transfer between lanes.

Transverse construction joints may serve as contraction joints if their location coincides with that of planned transverse contraction joints. If it is to be a contraction joint, a butt-type joint is formed by the header or transverse form and dowels are used for load transfer across the joint. Transverse construction joints not occuring at planned joint locations are generally tongue-and-groove joints provided with tie bars to prevent movement.

Expansion Joints

Expansion joints are usually transverse joints used to relieve expansion stresses in the concrete by providing a space where the concrete can expand if necessary. An expansion joint is created by inserting a non-extruding, compressible material as a filler between two slabs. The material should have sufficient strength to resist horizontal slab movement partially but permit such movement before crushing or buckling stresses develop in the concrete. A groove above the expansion filler is provided to receive joint sealing material.

Very few pavements are now built with regularly spaced expansion joints. Tests and experience have shown that closely spaced contraction joints provide adequate space for pavement expansion under normal conditions. Expansion joints are still used adjacent to bridges and other fixed structures in the pavement and at certain intersections.

Longitudinal Center Joints

Longitudinal center joints are generally provided in highway and street pavements other than those built in narrow lanes by the method known as "lane-at-a-time" construction. These center joints are intended to relieve the transverse stresses which develop from wheel loads and slab curling or warping due to moisture and temperature differential in the pavement. Longitudinal center joints are frequently referred to as hinge joints. They are not intended to open and close and tie bars are usually provided to prevent such movement.

Contraction Joints

Contraction joints are transverse joints used to relieve tensile stresses created by pavement contraction as the concrete cools and loses moisture. Contraction joints also relieve longitudinal stresses due to loads and curling and warping. They control the location of transverse cracking if properly spaced. Depending on spacing and other design considerations, these joints may or may not be provided with dowels for load transfer.

METHODS OF FORMING JOINTS

Hand-Formed Joints

The earliest method of forming joints in the surface of concrete pavement was by workmen using hand tools. Although this was in keeping with the hand methods of mixing and placing concrete in the early days, the practice of hand-forming and hand-tooling of joints extended well into the modern period of highly mechanized paving operations. Until about the mid-1950's, more joints were provided by hand methods than by any other means.

Limitations. —Although many miles of completely acceptable concrete pavements were built with hand-formed joints, the limitations of this method have become apparent in recent years. A critical limiting factor is the scarcity of skilled workmen. With the great expansion of concrete paving operations in highway and airport construction, workmen with adequate experience in the forming and tooling of joints have become spread too thin to produce dependable results on every project. Another factor is the speed with which modern paving equipment can place concrete. It is comparatively commonplace for a modern paving train to place a mile or more of 24-ft wide concrete pavement in one day. It would be a formidable task for a crew of finishers to provide joints in such a large expanse of paving by hand methods.

Hand-formed dummy groove joints (contraction and longitudinal center joints) have objectionable features which are probably inherent in the method. They are frequently of irregular width. They are often the source of bumps or depressions that cause pavement roughness. Concrete along the joints may be overworked with resultant poor durability. One of the major sources of trouble in dummy groove joints formed by hand methods has resulted from the template used to maintain the groove in the plastic concrete. Workmen may leave the template in place so long that the partially hardened concrete is fractured horizontally as the plate is lifted out. The thin layer of concrete above the horizontal crack may spall off under traffic, thus creating a serious maintenance problem.

Acceptable Uses of Hand-Forming. —Hand-tooling is the generally accepted method of finishing expansion joints and has provided completely satisfactory joints when properly accomplished. Expansion joints require that the expansion filler be installed ahead of the placing of concrete. It must be installed vertically and staked securely to the subgrade. Since most plans call for the expansion filler to be recessed ¾ to 1 in. below the pavement surface, some type of installation guide or cap is normally used in construction. This is generally a metal channel which fits over the filler and maintains it in a straight line across the paving lane. The cap is normally raised partially to permit edging of the concrete on both sides of the filler with a wide-flanged double edger, after which the cap is removed. The formed groove should be as wide as the filler and completely clear with no concrete bridging above the filler or at either end. The finished expansion joint should be checked with a straightedge to make certain no depression or hump has been created during the edging and finishing operations.

Hand-forming has been generally adequate for providing a groove for sealing both transverse and longitudinal construction joints, although sawing is generally considered more economical, is frequently used for this purpose, and may provide a smoother joint. Since construction joints will generally have tie bars to prevent movement, a shallow and comparatively narrow groove provides a sufficient reservoir for the joint sealer. Unless the reservoir is to be sawed, both sides of the joint should be edged during finishing operations. The groove for the joint sealer should be formed during the edging of the second slab or paving lane. Generally, a groove approximately $^3/_4$ in. deep and $^3/_8$ in. wide will be adequate for this purpose.

Sawed Joints

The practice of sawing joints in concrete pavement started about 1950 and became widespread in a relatively short time. The acceptance of this new method coincided very closely with the development of more efficient machines for placing and finishing concrete and the consequent speedup of paving operations. Use of the improved equipment to its full capacity became possible when joint forming was eliminated from the hand-finishing operations.

The early sawing operations were hampered by the limitations of the available sawing equipment. A brief quotation from an article by Robert Janowitz in the June 1959 issue of Roads and Streets will sum up the equipment improvement made in the first ten years of sawing operations:

> In the short span of ten years, many changes have taken place in concrete sawing. The early, low-powered, hand-pushed saws have given way to larger and more powerful self-propelled machines. The life of diamond blades has been extended greatly with the advent of tungsten-carbide bonds. Low cost, silicon carbide type abrasive blades can be used to cut green concrete in many places and have slashed cutting cost dramatically.

Application of Sawing.—Sawing has been successfully used for forming all types of joints in concrete pavement. Even expansion joints are sawed in England, though they are generally formed by hand in this country. The simpler and comparatively noncritical uses of sawing are for forming grooves at the top of construction joints and sawing longitudinal center joints. Since these joints are subject to little, if any, movement, the saw cuts can be of minimum width to permit effective sealing. Usually, a $^3/_{16}$-in. width has been found appropriate for this purpose.

Longitudinal construction joints can be grooved for sealing by sawing along the joint to a depth of $^3/_4$ to 1 in. or as provided by specifications. Sealing can follow closely after sawing and cleaning of the joints, a procedure that eliminates the necessity of a second cleaning before sealing. Transverse construction joints can be sawed in the same manner when they are tied, non-working joints. When the transverse construction joints are to function as contraction joints, the joint width provided should be the same as for other contraction joints.

Longitudinal center joints function similarly to contraction joints except that there is little movement in opening and closing of the joint. Experience has indicated that the sawing of the groove for these joints can be delayed until the concrete has hardened. It must be done before the pavement is opened to traffic—including construction traffic. To control cracking effectively, longitudinal center joints should have a minimum depth of one-fourth the slab thickness. They need have only the width required for sealing, approximately $^3/_{16}$ in.

Sawing has been used very successfully in providing longitudinal center joints. Because of the depth required, concrete saws operating in tandem have proved advantageous for sawing these joints. Sawing may be done with diamond or abrasive blades, using the most economical method for the particular aggregate. Usually the center joint can be flushed out, dried and sealed immediately after sawing, eliminating a second cleaning.

Sawing of contraction joints is the most critical operation performed in this method of joint forming. A quotation from the Navy specifications on joints indicates many of the factors to be considered in sawing contraction joints:

> The time of sawing shall be varied, depending on existing and anticipated weather condtions, and shall be such as to prevent uncontrolled cracking of the pavement. Sawing of the joints shall commence as soon as the concrete has hardened sufficiently to permit cutting the concrete without chipping, spalling, or tearing. If early sawing is the cause for under-cutting or washing of the concrete and the action is sufficiently deep to cause structural weakness or excessive cleaning difficulty, the sawing operations shall be delayed and resumed when directed. The sawing operation shall be carried on both during the day and at night as required regardless of weather conditions.

Since transverse contraction joints relieve tensile stresses which develop during early hardening and cooling, while the concrete is relatively weak, the reduction in cross-section does not have to be as great as in longitudinal center joints. Experience has shown that a depth of groove equal to one-sixth of the slab thickness or the diameter of the maximum size aggregate, whichever is greater, will generally control transverse cracking.

The exact time of sawing contraction joints depends on the type of aggregate, curing method, cement factor and weather. Generally all joints should be sawed in succession as soon as is possible without damaging the surface of the pavement. A slight amount of raveling should be permissible since it gives the operator a good gage of his timing. If there is no raveling at all, the concrete is probably too hard and cracks may develop ahead of the saw.

In some areas where very hard coarse aggregates are used, the cost of sawing joints may be prohibitive. A procedure to minimize the difficulty of sawing hard aggregates has been successfully used on a few projects. This consisted of vibrating a T-bar into the plastic concrete at the proper joint location. The vibrated T-bar laterally displaced the coarse aggregate from the saw-cut location and minimized the hard particles encountered by the saw after the concrete had hardened. Although this procedure may assist in sawing hard aggregates, it also adds an additional piece of mechanized equipment to the paving train and may increase the manpower requirement.

The sawing of contraction joints in concrete containing very hard aggregates, and particularly natural gravel, may produce a condition adjacent to the joints which is unfavorable to the durability of concrete. As the saw strikes the particles of hard aggregate, a vibration may be created by the saw action and aggregate resistance. This vibration may be severe enough to break the bond between the sawed stone fractions and the surrounding mortar. Since the concrete has hardened sufficiently that bond will not be reestablished, the damage is permanent. Some of the raveling and spalling of concrete occurring along sawed joints is probably due to this type of damage during sawing.

The width of sawed contraction joints will depend on the joint interval or length of slabs. Egons Tons and others have demonstrated that the dimensions of joints have a critical effect on the performance of joint sealers. This effect is covered by the term "shape factor." A joint width of 1/4 in. is generally adequate for the relatively short contraction joint intervals generally used in unreinforced concrete pavement. At the longer joint intervals usually specified when distributed steel is used in the concrete, wider contraction joints will be required. The general practice in sawing wide contraction joints is to use two passes of the saw to complete the joint. The first saw cut is narrow and to full joint depth. The second pass may be made with two saw blades separated by a spacer of proper thickness. The wider second cut is only of sufficient depth to accomodate the joint sealer material. Figure 2 illustrates two types of sawed contraction joints.

Advantages of Sawed Joints.--The sawing of joints has permitted the construction of much smoother concrete pavement than was possible when all joints were hand-formed.

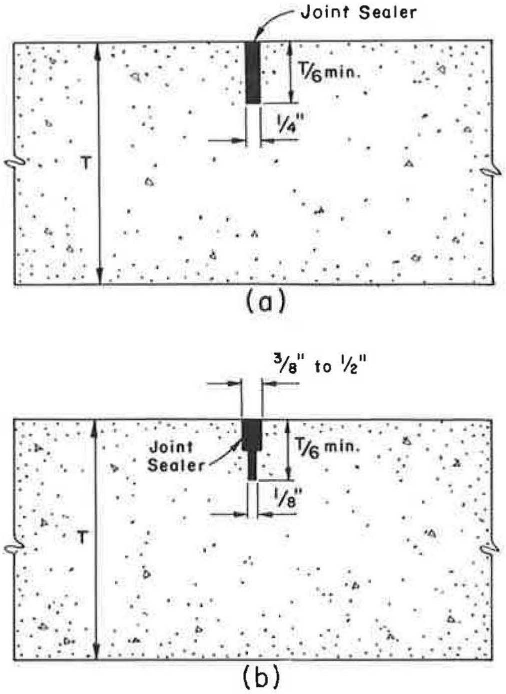

Figure 2. Sawed contraction joints in concrete pavement: (a) short joint intervals, and (b) long joint intervals.

Joint sawing has contributed to greater production of concrete pavement with less manpower which has resulted in overall economy. It has also helped to eliminate the overworking of concrete along joints with its consequent lack of durability.

Joint Inserts

The use of inserts for forming joints in plastic concrete is not new. Various devices and materials have been tried, some dating back almost to the time when joints were first used. A great many of these were found impractical or ineffective and were discontinued. Nevertheless, the principle of forming joints by use of inserts has persisted and some types are currently in use.

This report does not attempt an exhaustive review of the types of inserts that were tried and discontinued. Rather, the discussion is confined to the principal types used currently. It may be that some are omitted that are equal in importance to those discussed. The main purpose here is to explore the principle and its possibilities. The four types discussed may be seen in concrete pavements in various parts of the country.

Bituminous Ribbon Joints. —The use of preformed bituminous ribbon inserts started in the 1930's. The material consists of felt, $^{1}/_{16}$ or $^{1}/_{8}$ in. thick, impregnated with asphalt. Cut to proper dimensions for joint depth, the material is installed in the plastic concrete by special machines devised for the purpose.

When properly installed, ribbon joints have proved successful for longitudinal center joints and for contraction joints spaced at short intervals. Where the material was installed vertically, in a straight line and flush with the pavement surface, it has shown good performance over a long period of time. No edging, grooving nor sealing of the joint is required because the preformed ribbon serves as a complete and permanent joint filler.

A number of poor installations of ribbon joints have been reported and observed. The material has been installed on a slant, in wavy lines and at a depth below the surface of the pavement. Each of these faults contributed to pavement defects along the joints. The slanted material caused spalling, wavy alignment failed to control cracking and the buried ribbon caused spalling above it on the surface of the slab.

Deformed Metal Plate. --This patented device came into use in the early 1950's. It consisted of a galvanized iron plate with horizontal deformations or corrugations and was used for the dual purpose of forming the joint and providing mechanical interlock. The plates were pressed into the plastic concrete by a machine especially modified for the purpose. The plates were of proper width for installation $^{1}/_{2}$ in. below the surface and $^{1}/_{2}$ in. from the bottom of the slab. The slab surface was finished above the joint without grooving or sealing. Pavements built with this joint have not shown a good performance record. Extensive raveling and spalling along the joints have been reported. Use of this device appears to have been discontinued.

Sawed-Out Inserts. --This type of insert (Fig. 3) has been used for several years, though its use became more widespread in the middle 1950's. The inserts may be made of corrugated paraffin-treated paper, resin-impregnated fiber strips or premolded bituminous strips similar to expansion joint fillers. Boards of cane fiber and

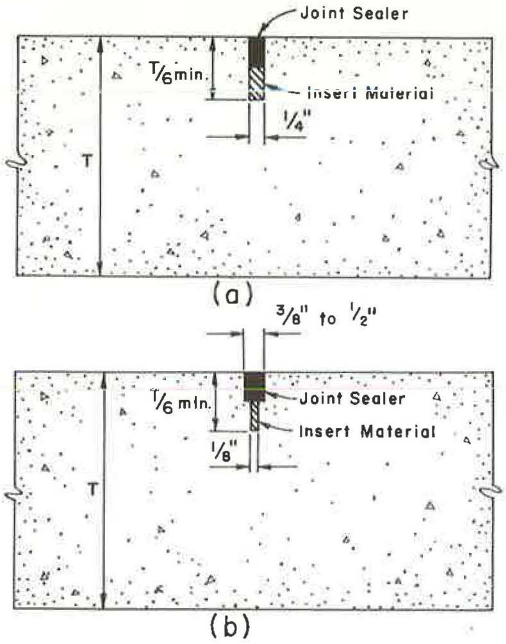

Figure 3. Sawed-out insert joints: (a) short contraction joint intervals, and (b) long contraction joint intervals.

a low asphalt content have also been successfully used.

The insert material is cut into strips of proper width to provide the specified joint depth. These strips are inserted in a groove formed by vibrating a T-bar into the plastic concrete behind the last mechanical finishing equipment. The insert is placed in the groove slightly below the surface and the surface over the joint is finished with a scraping straightedge. A crack will develop below the surface as the concrete hardens since it provides a plane of weakness. A fine crack will also develop above the insert which serves as a guide for the saw operator.

If bituminous impregnated strips are used, only the top $1/2$ to 1 in. need be removed for joint sealing, leaving the remainder of the insert as partial filler. Width of the groove should be at least the width of the insert and can be provided as wide as required to provide a proper shape factor for the joint sealer.

This type of insert joint has been used by some highway departments and on military and civil airport pavements. Both the Navy and Army Corps of Engineers permit its use. The joint acts as a positive crack control from the time the

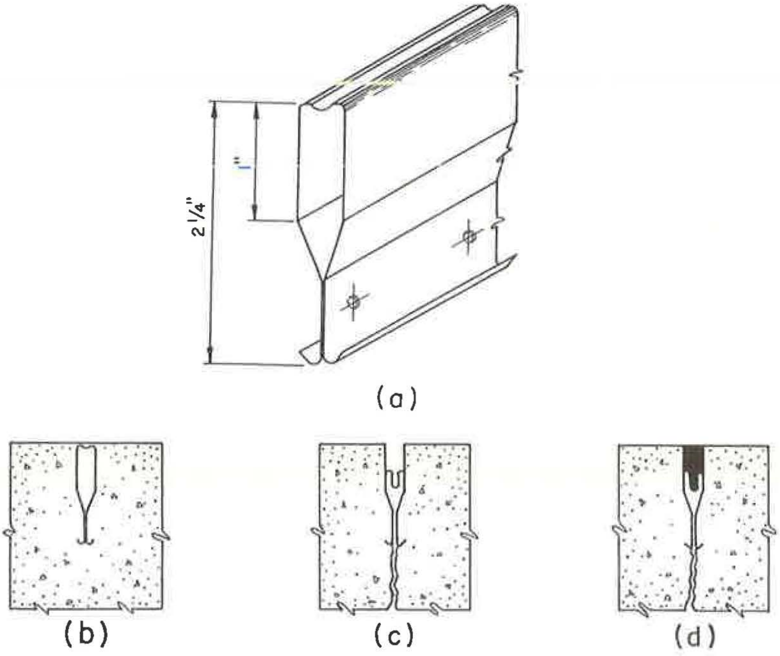

Figure 4. Tubular metal joint insert: (a) cross-section of $2\frac{1}{4}$-in. insert, (b) as installed, (c) after crimping, and (d) after sealing.

concrete is placed and sawing can be delayed until after all pavement is completed. Joint sealing can follow immediately after sawing and cleaning the joints.

Tubular Metal Joint Inserts.—The tubular metal joint insert is a comparatively recent innovation and its use has spread rapidly. The tubular device is fabricated from 30-gage galvanized steel to provide joint depths of 2, 2¼ or 3 in. with section lengths up to 13 ft. Sections of the material may be fitted together to provide a continuous length for use in longitudinal center joints. The shape of the device is illustrated in Figure 4.

The tubular insert may be inserted by hand into a groove vibrated into the plastic concrete or it may be installed mechanically with specially designed equipment. Styrofoam plugs are placed in open ends of the device to prevent the entry of mortar. The insert is installed so that its top is flush with or slightly below the surface of the concrete. After the concrete has hardened but before traffic is allowed on the pavement, the metal tube is crimped down to form a reservoir for joint sealer. This is done by a machine equipped with a wheel that enters the joint and crimps the tube to the proper depth. The ⅜-in. wide void created by crimping the metal tube is rectangular at the top and pointed at the bottom. The specified sealer should be applied immediately after the tube is crimped to prevent the entry of dirt or debris. Figure 4 shows a sequence of the device as installed, crimped and sealed.

This insert has been in use by some state highway departments since 1958. It has been used in highway pavements in several states and in airport pavements. It is included in the U. S. Army Corps of Engineers design criteria for airfield pavements. Joints formed by the tubular insert have a short service record at this time. Performance has been variable. The device appears to function better in pavements with short contraction-joint intervals than it does at longer spacings; joint spalling has occurred on pavements with the tubular insert installed at 60- to 100-ft intervals.

CONCLUSIONS

It appears that each of the methods of joint forming favorably commented on are adequate when used properly and under the proper conditions. Competent engineering judgment should provide the proper method or combination of methods required in a specific situation.

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A Study of Polysulfide Sealants for Joints in Bridges

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The polysulfide sealants used in expansion joints in bridges are commonly assumed to be perfectly elastic materials. This paper shows that these sealants are acutally viscoelastic and exhibit the interrelated phenomena of creep and stress relaxation. Curves are included for modulus of elasticity, creep, and stress relaxation, with shape factor, Shore hardness and temperature as parameters. Sample solutions are shown for the stresses in the sealants under various loading conditions, including tension plus shear and compression plus shear. A stress relaxation equation is derived using a curve-fitting technique and the stress relaxation relationship is verified by standard laboratory methods and by the method of photoelasticity.

•THE ENGINEER or scientist today, in dealing with the properties and behavior of solid materials, generally has at his command theories which, if not perfect, are at least acceptable and consistent. The engineer who worked with rubber-like materials had until recently no such assurance. It remained for the chemist and physicist correctly to postulate certain properties of highly extensible molecules before consistent theories were developed.

Although much of the significant work in this field has been done in recent years, the problem dates back almost 100 years and shows three distinct roots:

1. The general problem of flow in solid materials, beginning with the work of J. C. Maxwell;
2. Research in the field of rubber-like materials by such investigators as Treloar, Kuhn, Guth, Rivlin, and Tobolsky, dating back roughly 25 years; and
3. Specific works in the field of joint sealants, notably that by Tons (1).

Recent papers have shown a very intimate relation between the first two of these roots in the effort to explain the behavior of various polymers, including the polysulfide rubbers. Outside of Tons' work, very little effort has been made to apply this earlier work to the specific problem of expansion joints.

A study of this history brings two cases into focus, the perfectly elastic sealant and the material which flows with time. Since the polysulfide sealant can be formulated with a wide range of properties, both of these cases should be considered.

A joint sealant may fail mechanically in any one of the several ways shown in Figure 1:

1. The adhesive failure is a loss of bond between the sealant and the joint wall caused by a tensile load. It may start as a small localized failure and then peel rather rapidly under the action of stress.
2. The cohesive failure is a tearing of the sealant material, also under tension.
3. The extrusion failure occurs under the combined action of compression and traffic. The material under compression is extruded above the roadway surface and then folded and flattened under the action of traffic.

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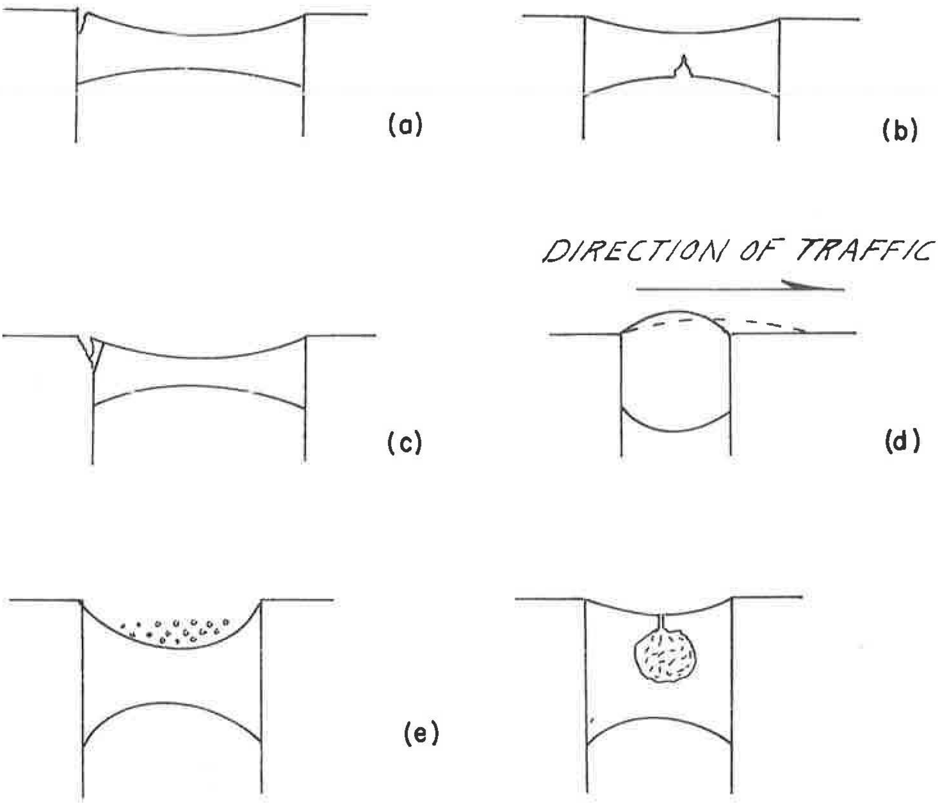


Figure 1. Types of joint failures: (a) adhesion, (b) cohesion, (c) spalling, (d) extrusion, and (e) intrusion.

4. The spalling failure is not, strictly speaking, a sealant failure, but its effect is just as destructive. In this case, the concrete adjacent to the joint interface spalls, generally under the action of heavy traffic, and the salt solution leaks past the sealant. The spalling failure is generally localized in the primary traffic lane but it breaks the continuity of the joint and quite often leads to a general peel-type adhesive failure.

5. The intrusion failure occurs under the combined action of extension and traffic. The sealant under tension necks down, forming a pocket, which fills with dirt. As the joint closes, this dirt is trapped within the sealer mass. This weak spot usually leads to a cohesive failure during the next extension cycle.

These failures are described in the literature. However, the present work demonstrates the extent of stress relaxation in the sealant, so two more failures attributable in large part to flow and stress relaxation are shown in Figure 2.

In each of the two cases shown in Figure 2, the sealant is loaded in normal fashion (either tension or compression) and then held at constant deformation until some degree of stress relaxation has taken place. On the next return cycle it begins deforming from this new shape and does not return to the original rectangle. In each case, a failure is imminent with additional cycling.

All these potential failures are accelerated by the effects of aging and weathering. However, the manufacturers of the various sealant materials are constantly striving to improve these products in their resistance to weather, salts, acids and solvents, so the effects of weathering will recieve no treatment here.

Each of the failure conditions mentioned presents a separate problem and the solutions may vary quite markedly, depending on the field conditions. The attempt being

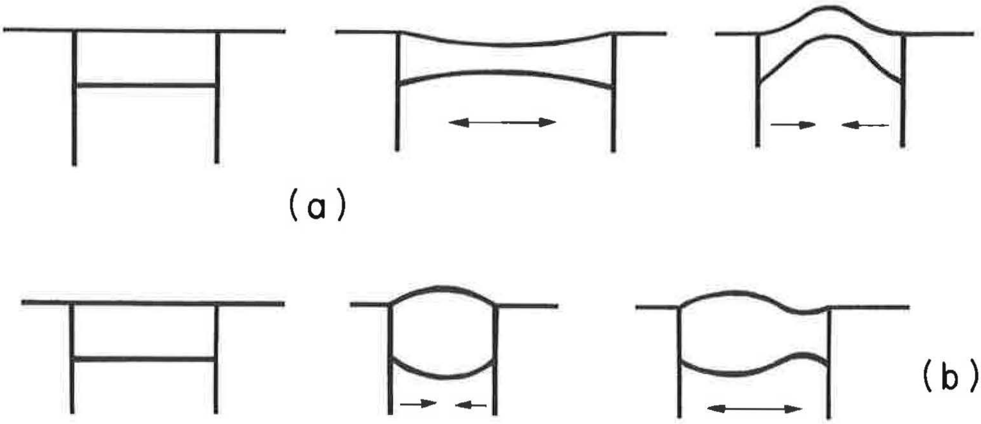


Figure 2. Change in sealant shape due to flow: (a) viscous tension-compression effect, and (b) viscous compression-tension effect.

made here is not to provide field solutions for all these problems but to evaluate the polysulfide sealant material; in the course of this investigation, the solutions of some of these cases present themselves.

PURPOSE OF STUDY

The purpose of this study was to consider the polysulfide sealant first as a perfectly elastic material and then as a flowing solid and to determine what stresses exist under load in a bridge joint. Inherent in this search, of course, was the determination of modulus and, what is more important, of the proper relationship between stress, modulus and strain, with time, temperature, shape factor and extensibility as the necessary parameters. Experimental work in this study included those tests which were necessary to establish the parametric relationships.

Appendix B of this paper includes sample solutions for the stresses in the sealant as follows: (a) considering the sealant as a perfectly elastic material--tension (or compression) alone, tension plus shear, and tension plus end rotation of the structure as caused by midspan deflection; and (b) considering the sealant as a flowing solid--tension (or compression) as caused by an imposed strain program corresponding to bridge movement.

THEORY

Sealant as a Perfectly Elastic Material

Many formulas have been presented in the attempt to show the proper relationship between stress, modulus and strain. Some have used the classical approach through the theory of rubber elasticity, and others have used an empirical approach. Treloar (2) has summed up the work of previous investigators and, working with an acceptable molecular model, has developed the kinetic theory expression in terms of extension ratios and the familiar shear modulus. The approach, which is made on a statistical basis using the entropy method, is explainable in terms of a mechanical model and lends itself to extension to the case in which the flow properties of the material are considered.

The internal work of deformation within a joint sealant according to Treloar's Kinetic Theory is expressed as:

$$W = \frac{1}{2} G \left[\lambda_1^2 + \lambda_2^2 + \lambda_3^2 - 3 \right] \qquad (1)$$

in which G is shear modulus and λ is ratio of extended length to the original dimension, in each of three directions. The external work done by the applied forces is

$$dW = f_1\, d\lambda_1 + f_2\, d\lambda_2 + f_3\, d\lambda_3 \tag{2}$$

Differentiating the internal work expression and equating it to the external work expression yields a set of simultaneous equations:

$$\begin{aligned} \lambda_1 f_1 - \lambda_3 f_3 &= G\,(\lambda_1^2 - \lambda_3^2) \\ \lambda_2 f_2 - \lambda_3 f_3 &= G\,(\lambda_2^2 - \lambda_3^2) \end{aligned} \tag{3}$$

These are the general stress-strain relations which hold within the range of the Gaussian probability function on which Treloar's statistical derivation is based. Practically speaking, these formulas are valid up to approximately 200 percent extension in the sealant.

These equations simplify when applied to the joint sealant problem because the joint extends across two or three lanes of traffic and, hence, has a length in this direction of 30 to 40 ft as compared to cross-sectional dimensions of approximately 1 in. With no loss of generality the extension ratio in this transverse direction can always be considered as unity.

Since the sealant undergoes no change in volume the following relationship must hold true:

$$\lambda_1 \lambda_2 \lambda_3 = 1 \tag{4}$$

Therefore, for a sealant under simple elongation the extension ratios are $\lambda_1 = \lambda$, $\lambda_2 = 1/\lambda$, and $\lambda_3 = 1$.

Since the only external force acting on the sealant is in the tensile (λ_1) direction, the stress reduces to:

$$f = \frac{dW}{d\lambda} = G\left[\lambda - \frac{1}{\lambda^3}\right] \tag{5}$$

Sealant as a Flowing Solid

In macroscopic terms, the viscoelastic behavior of polymers is usually separated into three components, instantaneous elasticity, delayed elasticity and viscous flow. Billmeyer (3) associates these properties with molecular structure as follows:

1. Instantaneous elasticity--stretching of the primary valence bonds and straightening of the bond angles in the main polymer chain (a reversible action);
2. Delayed elasticity--reversible uncoiling of the polymer chains and orienting them in the direction of the stress; and
3. Viscous flow—irreversible slipping of the chains past one another.

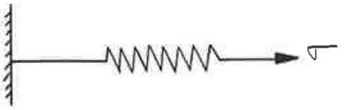
These actions are, of course, stated in completely general terms and the interrelation between them is a function of other parameters such as temperature.

To the laboratory observer, the essential difference between the elastic and the viscoelastic body is that the latter shows the two interrelated phenomena of creep and stress relaxation. Both of these phenomena are capable of explanation in terms of molecular structure. The mechanism of creep, which is demonstrated later, becomes apparent when a creep curve is shown together with the model movements which represent the behavior.

The method of analogous mechanical models has been selected for use in this present work because it defines the behavior of the material in a manner which can be logically explained in terms of the molecular structure of the polymer. The method is said to be an approximation but Billmeyer (3) and many others feel that because of its sound basis in molecular theory, it offers the best solution currently available.

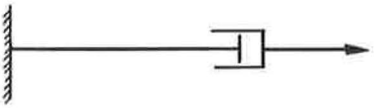
The model method consists of the identification of molecular behavior with certain types of response to an applied stress. These responses are then represented by simple mechanical models which can be explained in mathematical terms. An ideally elastic material is represented by a spring, which obeys Hooke's law, that is, stress proportional to strain (Fig. 3). A completely viscous response is represented by the hydraulic dashpot (Fig. 4). For this element, stress is proportional to strain rate. The third basic element, the friction unit, shows no movement until stress reaches some limiting value represented as a friction force (Fig. 5).

Certain basic combinations of these units occur so often that these combinations are considered almost as elements. The series combination of a spring and a dashpot is known as a Maxwell model (Fig. 6) and represents a material which shows an instantaneous elasticity and a straight-line creep under load and some amount of flow or permanent set on removal of the load. The parallel combination of a spring and a dashpot is known as a Kelvin (or Voigt) unit (Fig. 7), which represents a material displaying a damped or delayed elasticity under load but no permanent set on removal of the load.



$$\sigma = G\epsilon$$

Figure 3. Model for ideally elastic material.



$$\sigma = \eta \frac{d\epsilon}{dt}$$

Figure 4. Model for viscous flow.

$\sigma < \sigma_0$ NO MOVEMENT

$\sigma > \sigma_0$ YIELD

Figure 5. Friction model.

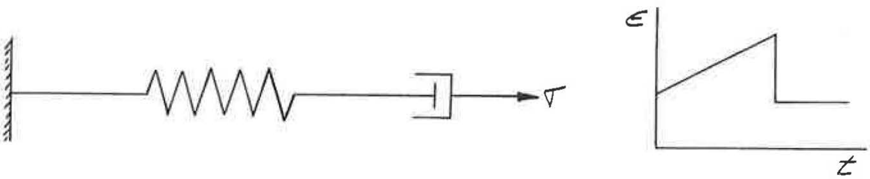


Figure 6. Maxwell model.

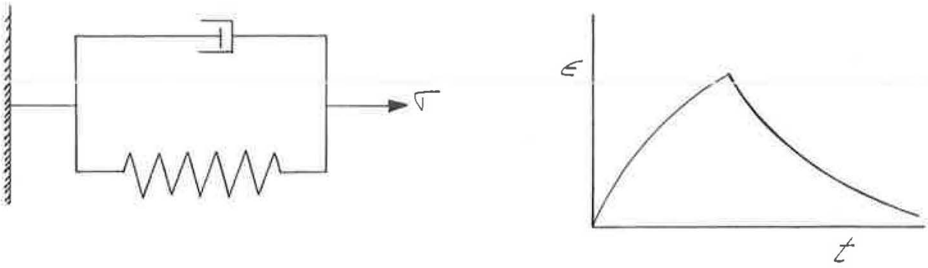


Figure 7. Kelvin model.

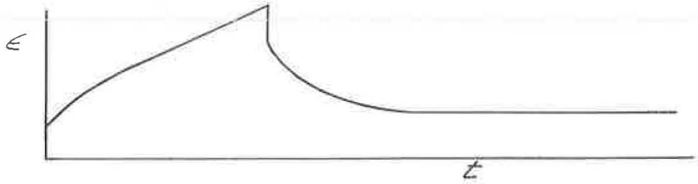


Figure 8. General creep curve.

To describe a material with a model system we must know which basic elements are present and what combinations exist. A creep curve (strain vs time at constant load) for the material in question will generally establish the presence of springs and dashpots in a system. The friction element can be identified by plotting various load-increment curves of elongation vs time.

The creep curve for the polysulfide rubbers, shown in Figure 8, duplicates the curve shown in many texts as the generalized curve for all rubbery polymers. Comparison of this curve with the creep curves of the Maxwell and Kelvin units immediately suggests an additive combination of the Maxwell and Kelvin units with a four-element model to describe material behavior. The presence of a yield point (friction unit) is ruled out by creep tests at very low stress levels. (One such laboratory specimen was still deforming after 6 months at only 1.3 psi).

For clarity the creep curve is reproduced in Figure 9 to a distorted scale and the actions of the model elements associated with each part of the curve are shown below the curve. This curve really represents a family of curves with different magnitudes corresponding to different Shore hardness values and shape factors. The stress levels used are quite low (5 to 10 psi). On application of load, there is an instantaneous deformation ϵ_0 (a spring element) and then a curved section which is delayed elasticity (a Kelvin unit), a straight-line flow with time (a dashpot) up to the unload point. On removal of the load, these actions appear in reverse: an elastic snapback ($= \epsilon_0$), a delayed recovery and some permanent set.

The four-element model is the simplest model to describe the material behavior, but many authors, including Billmeyer (3), Treloar (2) and Alfrey (4), state that this is an oversimplification and should be used with caution, because it applies only to a material with a single stress relaxation time. The polymers, in general, exhibit stress relaxation but the details of the stress relaxation process depend on the multiplicity of ways in which the molecules can regain their most probable configurations. Consequently, there are so many modes of relaxation that the spectrum of relaxation times can be approximated by a distribution function. If there were but a single relaxation process, the rate of stress decay would be a simple exponential function. However, Stern and Tobolsky (5) in a specialized study of polysulfides have established that this particular polymer differs from the rest of the rubbery polymer group in that it does exhibit a single stress relaxation time. This contribution, together with the creep curve, should establish the four-element model as an adequate approximation to

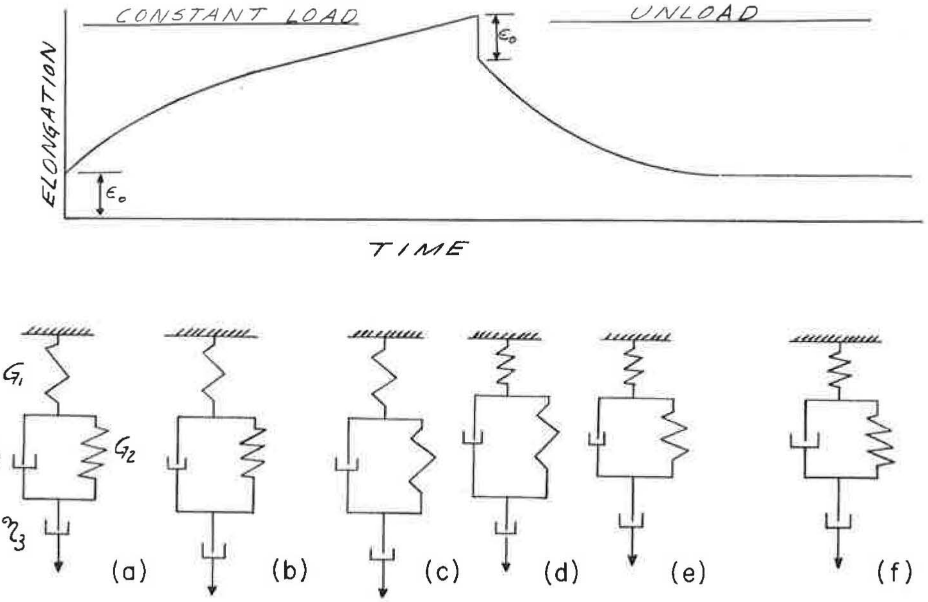


Figure 9. Model movements: (a) spring G, deformed, (b) Kelvin unit and η_3 deforming, (c) η_3 still deforming, (d) spring G, recovered, (e) Kelvin unit recovering, and (f) η_3 remains deformed.

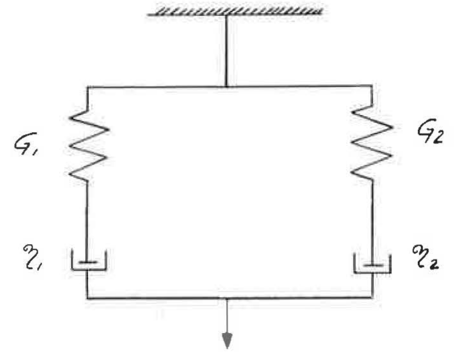


Figure 10. Equivalent model (Model B).

describe the action of the viscoelastic joint sealant under load. Strictly speaking, in a material with a true single relaxation time, no creep recovery would be expected at the termination of a stress relaxation experiment. Actually, a small amount of creep recovery was noticed but was considered not sufficient to invalidate the approximation.

The basic four-element model is excellent for demonstrating the three characteristics of polymer behavior, i.e., instantaneous elasticity, delay elasticity, and flow. This model is conveniently solved for strain when an imposed stress on the system is specified. However, for the more practical case of solving for stress under an imposed strain program, it is more convenient to substitute an equivalent model than to solve the basic model. The equivalent model shown in Figure 10 is related to the basic model through a set of equivalency equations included in Appendix B with sample problem solutions.

The basic equation for stress taken from the model is

$$\sigma = \left[\beta\eta_1 + e^{-t/\tau_1}(G_1\epsilon_o - \beta\eta_1)\right] + \left[\beta\eta_2 + e^{-t/\tau_2}(G_2\epsilon_o - \beta\eta_2)\right] \qquad (6)$$

in which

β = strain rate,
η_1, η_2 = viscous constants taken from the creep curve,
G_1, G_2 = elastic constants taken from the creep curve,
ϵ_0 = initial displacement,
τ_1, τ_2 = relaxation times (defined as the time necessary for the stress in the material to decay to 1/e times the initial stress), and
t = time.

A complete development of the stress equation has been given previously (6).

EXPERIMENTAL WORK

The materials used in this work were all two-component cold-poured polysulfide rubbers. All materials were commercial grade, in quart or gallon containers, and were donated by the manufacturers. Polysulfide joint sealants are marketed with values of Shore hardness ranging from 5 to 50. Since New York State currently specifies a Shore range from 10 to 15 for bridges and pavement joints, only those materials in and around this range were selected for test. The sealants are available in both gray and black and both types were used without distinction. The sealants were grouped into three categories by hardness: the soft range (Shore hardness 3 to 8), the medium range (8 to 16), and the hard range (16 to 22). One set of modulus tests used a material with a hardness of 30. All hardness measurements were Shore A.

In all, eight tests were conducted. Two of these were to confirm the assumptions made in Tons' paper, i.e., the constant volume assumption and the parabolic neckdown assumption. The other tests were of cycling tension and compression, creep, modulus of elasticity, stress relaxation, photoelastic correlation, and peel strength.

Flexible sealants for joints have many applications in industry which necessitate a wide range of sizes and shapes for the sealant. Since the present work was concerned with the expansion joints in bridges, only those shapes which might be applicable to this specific use were included. In all, eight sizes were included in each test, ½- and 1-in. wide specimens in joint depths of ½, 1, 1½ and 2 in. Each test was performed in each of the Shore hardness ranges and, in most cases, was repeated with materials from at least two manufacturers in each range. Thus, the creep test, for instance, would involve the testing of 16 specimens in each hardness range or 48 specimens in all.

Description of Experiments

The constant volume assumption was checked in a triaxial compression tester in the Rensselaer Soil Mechanics Laboratory. The apparatus is standard in soils work and will not be described in great detail here. It consists of a hollow plastic cylinder filled with water into which the specimen is placed. Loading is accomplished by a 1-in. diameter plunger extending through the top cover plate. A graduated tube to show differences in water level is used as a reading device.

The parabolic neckdown assumption was checked by using an Ames dial gage as a depth indicator. A sealant specimen mounted on concrete blocks was placed in the cycling machine and extended. The Ames gage was mounted in a wooden block with the plunger extending downward. The block was then placed on top of the concrete test blocks across the extended joint. The amount of neckdown of the extended sealant was read directly from the dial gage. The cycling tension and compression test was performed in a machine designed and built specially for the purpose by R. J. Schutz. Specimens for this test were prepared with concrete test blocks. Lengths of the block and, consequently, of the specimen were 3 in. and the joint depth was variable up to 2 in.

The creep test, which furnishes the constants for the stress equation, was accomplished by static loading. Specimens, 6 in. long, were formed between sections of 2 by 2-in. aluminum angles, $7\frac{1}{2}$ in. long. Creep curves, which are plots of strain vs time at constant load, were plotted for a range of shapes, loads and hardness values. The curves are included in Appendix A.

Specimens for the modulus of elasticity test were identical with the creep specimens. The test was performed in a 30,000-lb capacity pendulum-type Riehle testing machine. The modulus curves plotted by the machine in units of load vs deformation and with a change in scale only are also included in Appendix A. Strain rate for the modulus test was 0.1 in./min.

The load-deformation (or stress-strain) curves for these materials were, of course, nonlinear functions and the value of modulus used for computation was the value of stress at 100 percent strain.

The stress relaxation test yielded a plot of stress vs time at constant strain. A constant strain of 50 percent was used throughout the work. The test was performed on the same pendulum machine as the modulus test.

The photoelastic work consisted of a verification of the stress relaxation time as determined on the pendulum machine. Specimens were 1 by 1 in. in cross-section and 6 in. long. The material was a translucent polysulfide epoxy with the manufacturer's formulation adjusted to vary the Shore hardness. Creep curves were plotted and then identical specimens were tested on the pendulum machine and in the polariscope (Appendix A, Figs. 29 and 33).

The peel test used was somewhat similar to the ASTM Peel Test. The sealant was spread on 1- by 6-in. rigid substrate. A 1-in. wide strip of heavy canvas was impregnated with sealant and then placed on the substrate and rolled until the depth of sealant and canvas was $\frac{1}{16}$ in. The canvas strip was then folded back through 180° and the canvas and rigid strip were placed in opposite jaws of the pendulum machine. The rate of peel used was 3 in./min and maximum load was read directly from the machine.

DISCUSSION

The sample problems for the elastic sealant (Appendix B) illustrate that shear, when combined with extension, may be neglected for all practical purposes. However, shear in combination with compression of the sealant produces a dangerous condition. Midspan deflection of a bridge structure is shown to produce practically no shear but does increase the tensile strains in the sealant by as much as 25 percent.

Leadermann (7) describes time as the main character in his work on creep of polymers. This same description might be paraphrased by stating that in dealing with joint sealants, time has been the forgotten parameter. The sample problems shown in Appendix B indicate that when time, or better stated, when stress relaxation enters the picture, stresses in the sealant drop to almost negligible values. The problem then becomes one of shape and recovery rather than stress.

In addition to the tests mentioned previously, curves included in Appendix A show the variation of hardness with temperature and the variation of modulus of elasticity with hardness. All experimental work in the present investigation was done at room temperature and these curves mentioned are an attempt to extrapolate these results to other temperature values. For example, if it is desired to use a sealant which has a hardness of 5 at room temperature for some application at -30 degrees its behavior can be predicted. At this temperature, the A-5 material has a hardness of 20. The creep, modulus of elasticity and stress relaxation values can be found from the respective curves for the A-20 material. This extrapolation method is admittedly a limitation on the present study but it represents at least a starting point for predictability.

The creep curves included afford a measure of creep predictability. The higher modulus materials show a much better compliance with the creep curve shape than the softer materials. All curves are shown as smooth curves, but the softer materials are quite erratic in behavior, and the curves represent the average of many retests and the elimination of some obviously faulty values.

It must be remembered that when a structure moves, the forces exerted on the sealant are quite high and the sealant must comply with the imposed strain program.

It may seem ridiculous to state that the sealant never moves the structure, but at this time many spalling failures are blamed on the sealant because it pulled the concrete apart. The values of creep, modulus and stress relaxation included here should help to dispel this notion. A spalling failure is simply due to poor concrete, not a strong sealant.

The creep behavior does vary with shape. Under equal stresses, a shallow seal will creep more than a deep one. This result is not surprising when compared to the parabolic length of the sealant. It is also important that within the 200 percent strain limitation the creep curve will superimpose when subjected to a variation in stress. More research is needed to determine whether the new polysulfide formulations show any tendency towards work hardening under repeating cycling.

The modulus curves are purposely left in terms of load vs elongation to make them easily readable. When plotted as nominal stress-strain curves (stress based on original cross-sectional dimensions), they are virtually coincident which shows that modulus values are practically independent of shape. The modulus value by definition is stress at 100 percent strain. The modulus values are plotted for a strain rate of 0.1 in./min. They will vary with strain rate because the steep gradient of the modulus curve at the beginning of the test corresponds to the steep downward gradient of the stress relaxation curve for very short times.

No values of ultimate cohesive strength are reported because of the fear of erroneous interpretation. Every sealant tested was extended well beyond 200 percent strain, and some as far as 1,000 percent, before failure. Above 200 percent strain neckdown is no longer parabolic and cross-sectional area reduces to almost zero. Consequently, any stress (which is load divided by area) would show values so high that they appear ridiculous.

The stress relaxation curves are perhaps the main contribution that this paper has to offer. The curves follow a generally exponential shape. Tobolsky (5) has shown that the polysulfides in general follow the relation:

$$f = f_o \exp -k't \qquad (7)$$

He states that the curve is, in general, steeper than exponential and relates k' to the rate of bond rupture. His method for finding k' is a curve-fitting technique. The experimental curves offered here are also steeper than exponential and a curve-fitting scheme is also used. The equation which fits the curve is really a family of equations of the form:

$$f = f_o \exp \ (t/\tau)^n \qquad (8)$$

in which n varies with τ. For low values of τ (about 1 hr), n approaches unity. For higher values of τ, n varies between 0.5 and 1.0. The highest value of τ obtained in this work was 6 hr. This was for a high modulus sealant. The middle range (A-12) sealants showed a relaxation time of 3 hr. The erratic soft-range materials showed great variation in values and also wide variation for single points on each curve. Further study of stress relaxation should lead to a definitive relationship by which τ and n could be predicted for different sealants.

The important fact to be recognized with polysulfide sealants is the order of magnitude of the stress relaxation time. In just a few hours after an imposed strain, the stress has relaxed to less than half of its initial value. The fact that the relaxation is steeper than exponential is also noteworthy. In the event of an imposed strain (ϵ_o) of large value, the sealant can actually relieve the stress by as much as one-third within the first 20 min.

The peel test used was, to some extent, new and needs refinement. The test specimens, 1 in. wide by 6 in. in gage length, were $\frac{1}{16}$ in. thick. Eleven of the twelve specimens tested did not actually fail by peeling away clean from the substrate but by tearing of the sealant. The average value of tearing strength was 42.5 lb for the 1-in. wide strip at a testing machine rate of 3 in./min. This value is very close to the values of peel strength and tear resistance which are available from the various manufacturers. Further work on the peel test should include an investigation of the effect of specimen thickness and also a long-time test at low loads, somewhat after the fashion of the Bikerman (8) test.

The results of the photoelastic work have to be classed as both good and poor. The original intention was to find a birefringent material with the same properties as the actual sealant to make a comparative study. Finally, several formulations of epoxy-polysulfide combinations were developed in the desired hardness ranges, but these showed a shorter relaxation time, a faster creep rate and more permanent set than the actual sealants. Differences were expected, of course, but it was hoped that a proportionality constant could be derived such that actual stresses in a sealant could be checked by photoelasticity. However, the characteristics of the photoelastic material are somewhat contradictory when compared to sealant behavior. More research is needed to determine the factor which can be applied to the two materials so that a quantitative prediction can be made.

The success achieved with the photoelastic method was the development of several materials which exhibit stress relaxation according to an exponential law. Identical specimens of material were tested in the Riehle machine and the polariscope; both of these tests show very good agreement with the theoretical curve. Quantitative values for the photoelastic curve were obtained by counting the total number of stress fringes which passed a given point during the rapid loading process and equating this fringe order to the maximum load value shown by the testing machine. One end of the specimen was blocked at a constant 1 in. width and the other end of the specimen was strained to 25 percent. This method of obtaining clear fringes assumes a linearity of stress in the specimen. This linearity should be checked by strain gaging if the method is to be used further.

Since so much emphasis has been placed on shape, some new shapes were tested to find one which would not extrude above the roadway surface. Two such shapes are shown in Figure 11. The trapezoidal joint would help to eliminate spalling failures, but it also makes a wider joint and, consequently, would cause a car to make an objectionable thump when riding over the joint. When formed with a flush top, this joint extrudes above the roadway surface, but not in a parabolic shape, under compression loading. When formed with a slight depression in the surface, the sealant no longer extrudes under compression, but the poor riding quality is still objectionable.

The hollow shape shown in Figure 11 is actually formed by filling the joint to half depth, inserting a dumbbell-shaped strip of soft urethane foam, and then filling the joint. For wide joints (1 in. and wider) such as might be encountered in bridge work, this shape has possibilities. However, because it is difficult to form and the foam has a tendency to float, the few specimens tested showed rather erratic behavior. These problems might be solved by experiment and experience.

The ordinary rectangular shape formed with a depression in the top also offers possibilities. This shape does not extrude above the roadway for shallow joints. Deeper joints do tend to bulge upward under compressive loads.

RECOMMENDATIONS

Although the polysulfide sealants have many properties which make them desirable as sealants, such as high bond strength, extensibility, and excellent short-term mem-

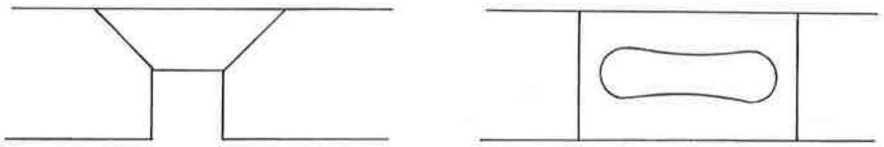


Figure 11. Experimental joint shapes.

ory, the sealant problem is not yet solved. There are many aspects of sealant behavior that have not yet been investigated. Among the many questions still to be answered are the following:

1. What effect does work hardening have on the physical properties of a sealant?
2. Does the aging and weathering of a sealant affect its mechanical behavior?
3. What is the response of a sealant in a skewed expansion joint?

A great deal of additional research is necessary so that these and other vital questions may be answered, not only in terms of the polysulfides, but also with the other available sealant materials.

ACKNOWLEDGMENTS

The complete study from which this paper was taken was presented as a Doctoral Dissertation at Rensselaer Polytechnic Institute. The author wishes to extend his thanks to Professors Egons Tons, J. F. Throop, J. T. Watkins, J. Hollingsworth, R. H. Trathen and R. M. Lewis for their encouragement and direction.

The joint sealant industry on the whole has been very helpful. Particular thanks are extended to Raymond Schutz, Sika Chemical Corp.; C. A. Peters, Allied Materials Corp.; Norbert Hochreiter, H. B. Fuller Co.; Joseph Amstock, Products Research Corp.; Aaron Kaplan, Lewis Asphalt Engineering Co.; H. V. Wittenwyler, Shell Chemical Co.; and A. Shuman, Polarizing Instrument Co.

The author's deepest debt is to Harold B. Britton of the New York State Department of Public Works, without whose constant faith, encouragement and material assistance the project never could have been undertaken.

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Appendix A

GRAPHICAL RESULTS

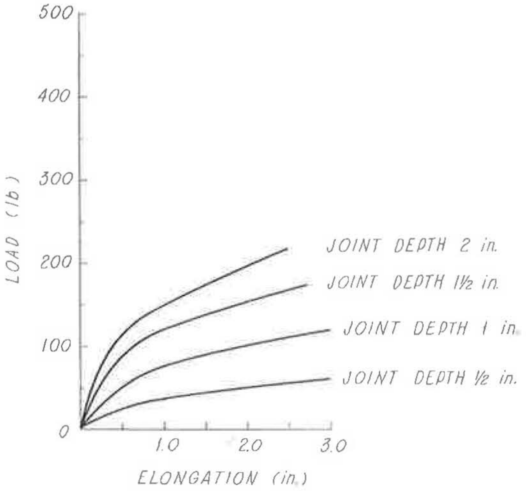

Figure 12. Load elongation curves; Shore A-5, ½-in. wide joint.

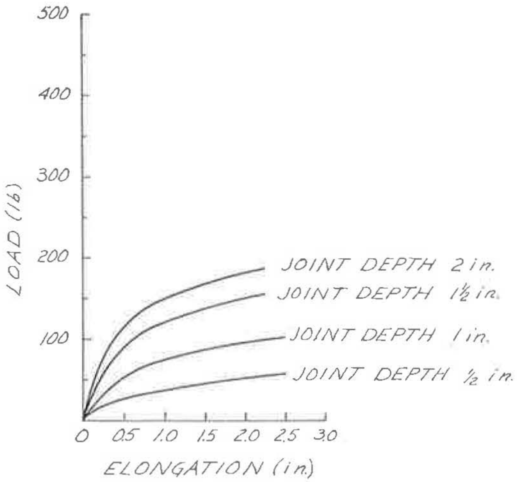

Figure 13. Load elongation curves; Shore A-5, 1-in. wide joint.

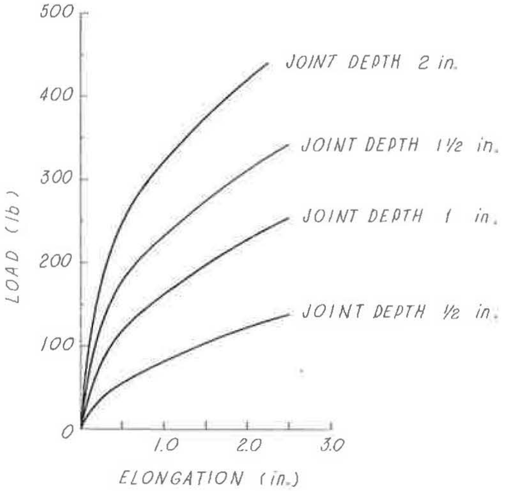

Figure 14. Load elongation curves; Shore A-12, ½-in. wide joint.

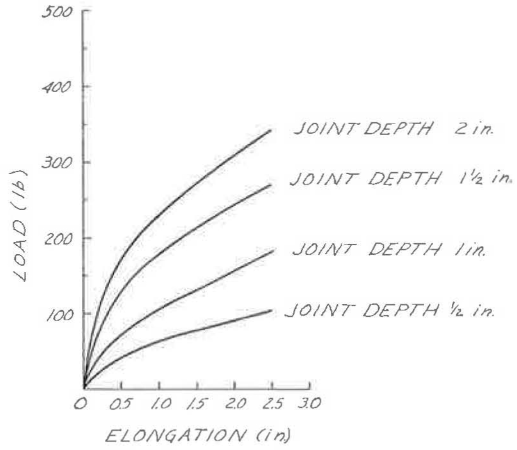

Figure 15. Load elongation curves; Shore A-12, 1-in. wide joint.

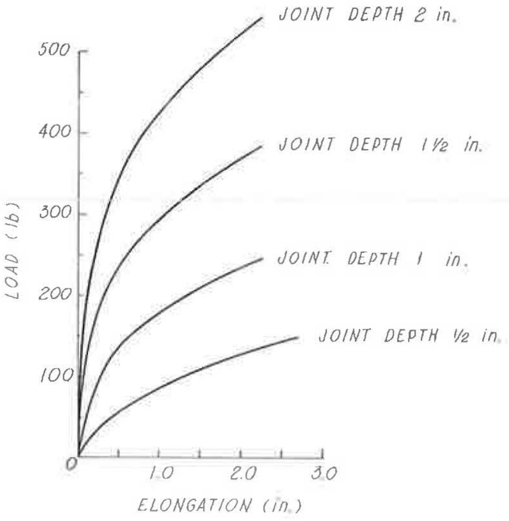

Figure 16. Load elongation curves; Shore A-20, ½-in. wide joint.

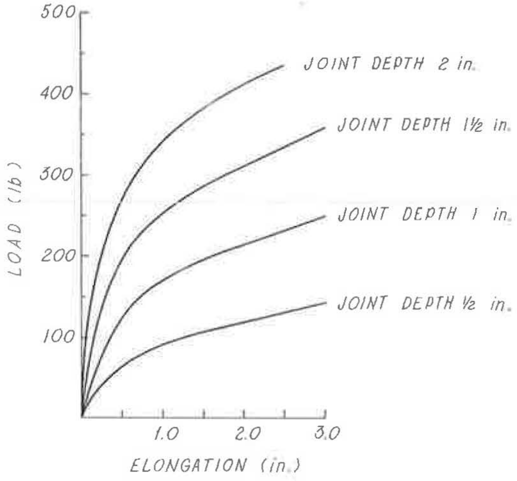

Figure 17. Load elongation curves; Shore A-20, 1-in. wide joint.

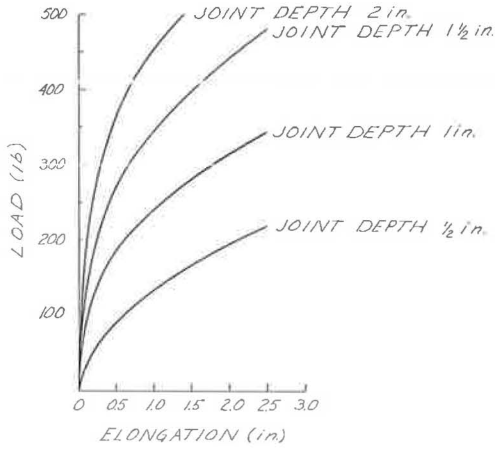

Figure 18. Load elongation curves; Shore A-30, ½-in. wide joint.

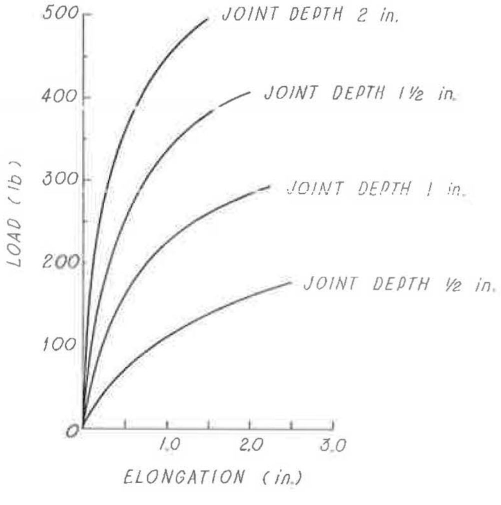

Figure 19. Load elongation curves; Shore A-30, 1-in. wide joint.

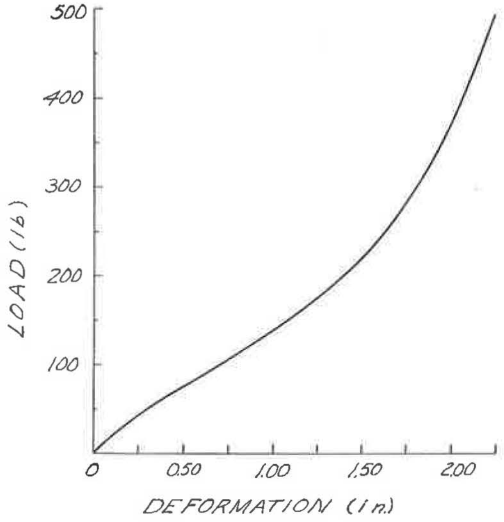

Figure 20. Load-deformation curve—compression; Shore A-12, 3½-in. diameter, 4-in. high specimen.

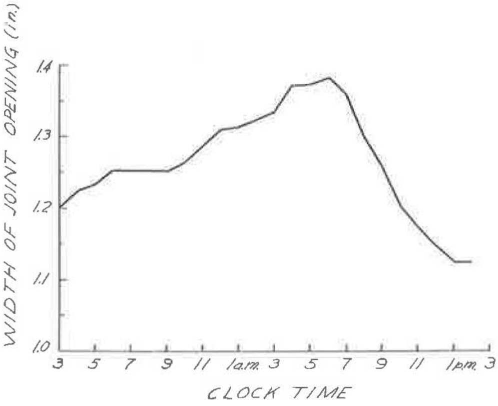

Figure 21. Rate of bridge movement; normal joint width 1in. at 76 F, 100-ft bridge span, 22 to 66 F temperature variation.

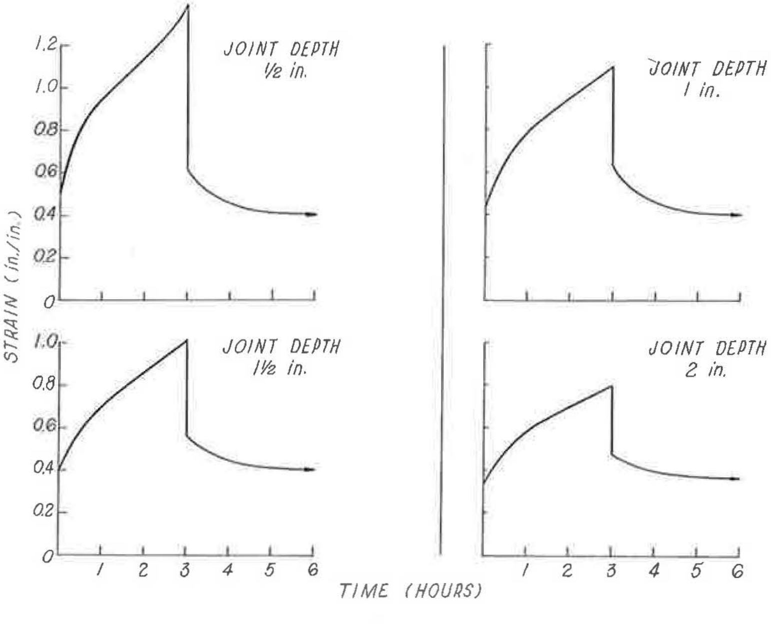

Figure 22. Creep curves; Shore A-5, $\frac{1}{2}$-in. wide joint, 8-psi constant load.

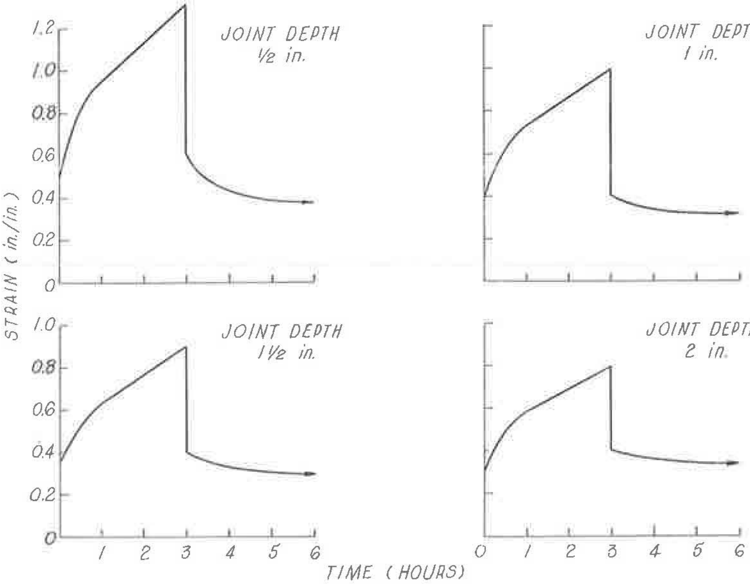

Figure 23. Creep curves; Shore A-5, 1-in. wide joint, 4-psi constant load.

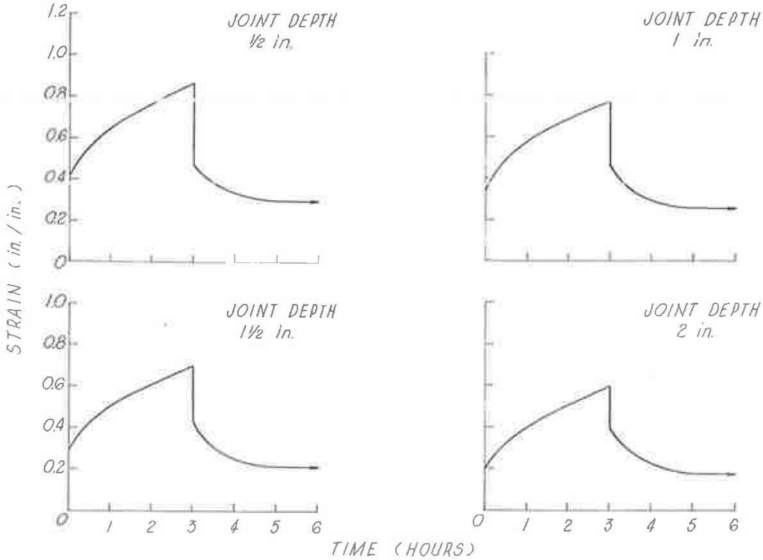

Figure 24. Creep curves; Shore A-12, $\frac{1}{2}$-in. wide joint, 12-psi constant load.

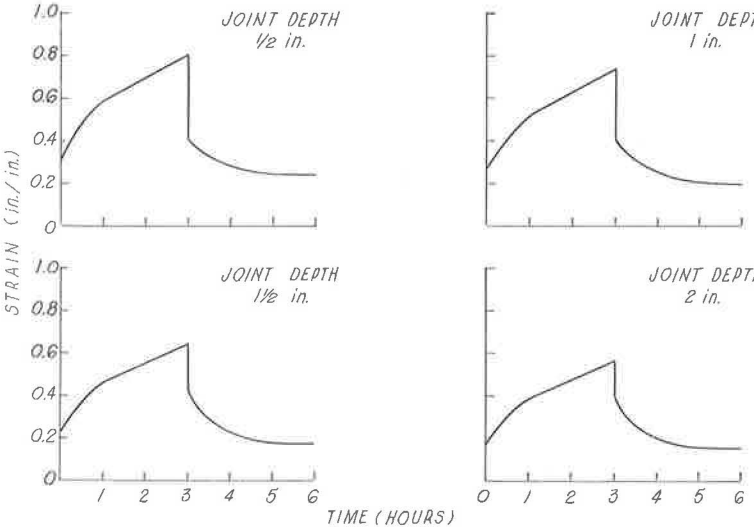

Figure 25. Creep curves; Shore A-12, 1-in. wide joint, 6-psi constant load.

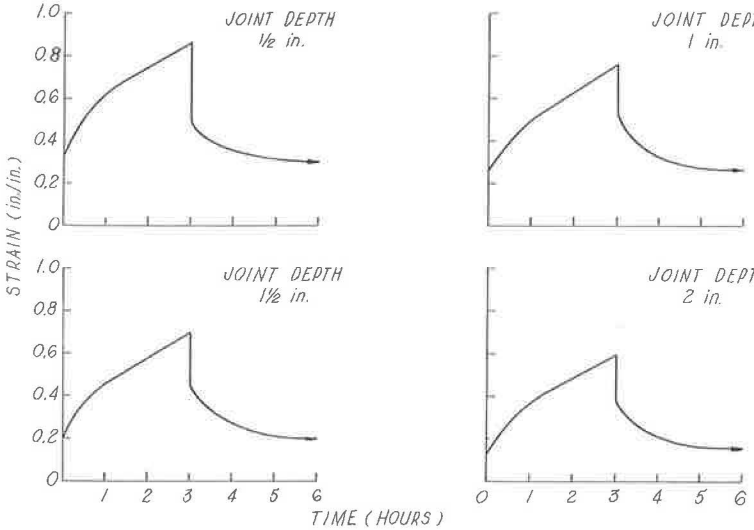

Figure 26. Creep curves; Shore A-20, $\frac{1}{2}$-in. wide joint, 16-psi constant load.

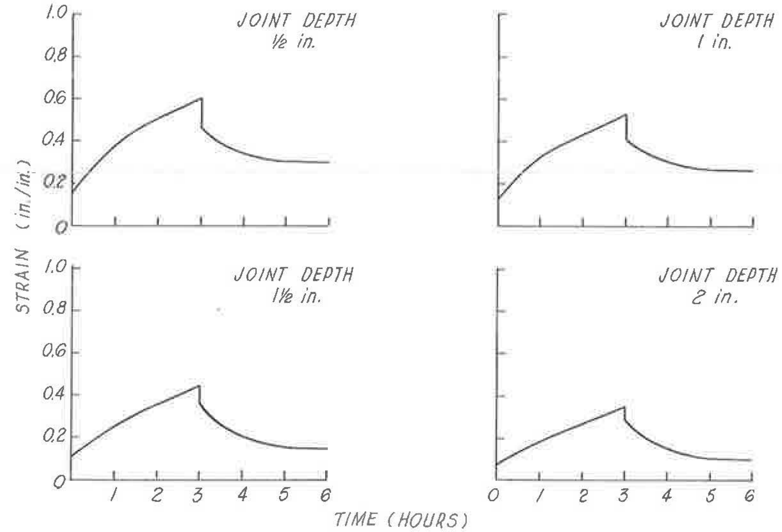

Figure 27. Creep curves; Shore A-20, 1-in. wide joint, 8-psi constant load.

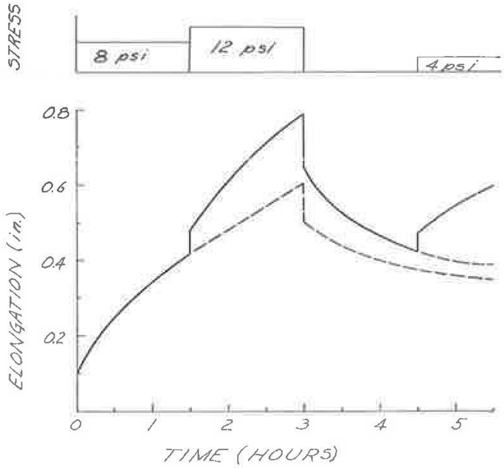

Figure 28. Boltzmann superposition curve; Shore A-12, 1-in. wide joint.

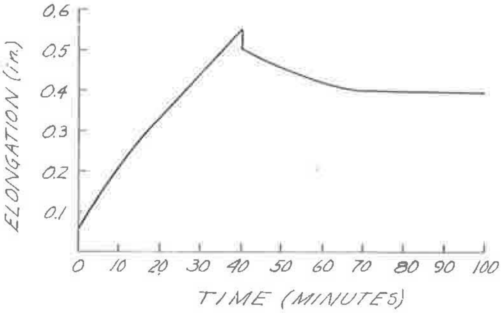

Figure 29. Creep curve—photoelastic specimen of clear polysulfide epoxy; Shore A-20, 1- by 1- by 6-in. specimen.

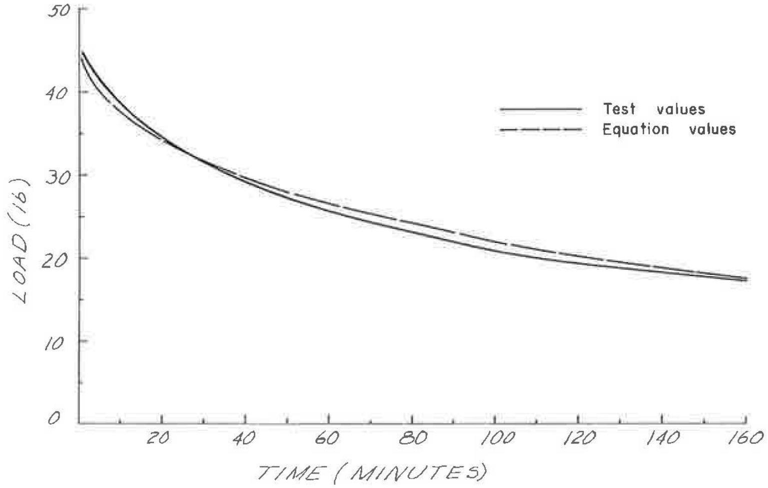

Figure 30. Stress relaxation curves; Shore A-5, $f = f_o \exp (t/\tau)^{0.6}$ where τ = 180 min.

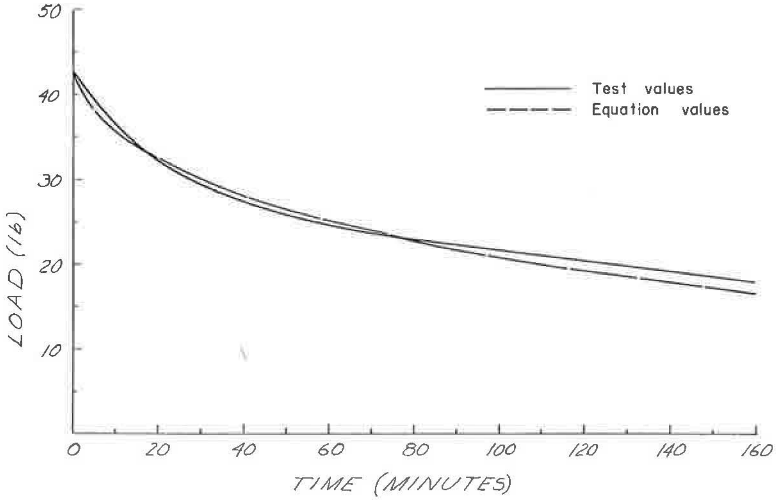

Figure 31. Stress relaxation curves; Shore A-12, $f = f_o \exp (t/\tau)^{0.6}$ where τ = 180 min.

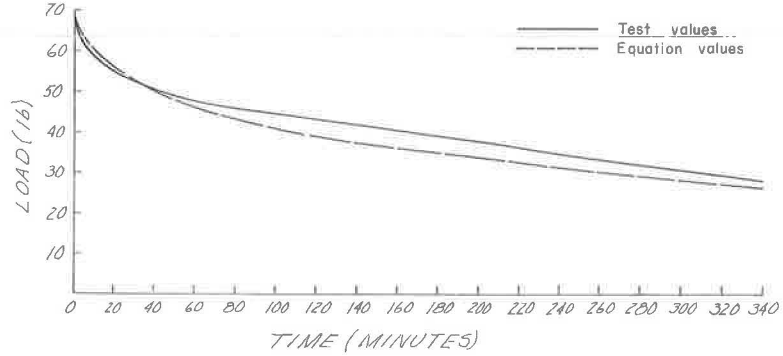

Figure 32. Stress relaxation curves; Shore A-20, $f = f_o \exp -t/\tau)^{0.5}$ where $\tau = 360$ min.

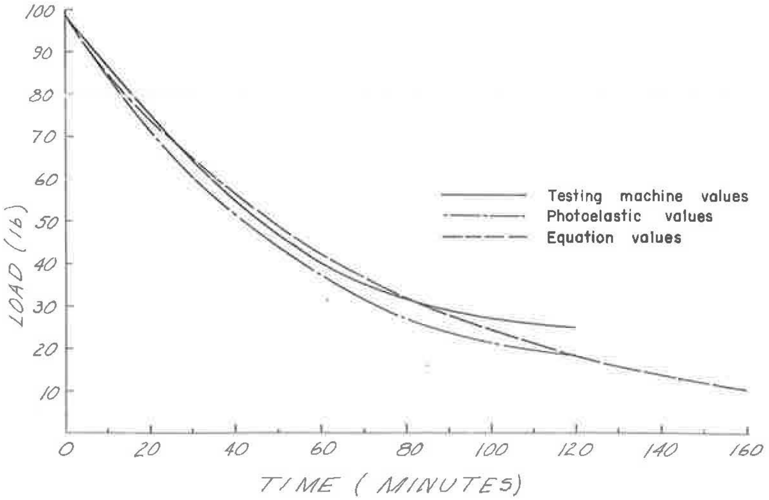

Figure 33. Stress relaxation curves--photoelastic specimen of clear polysulfide epoxy; Shore A-20, 1- by 1- by 6-in. specimen, 25 percent constant strain.

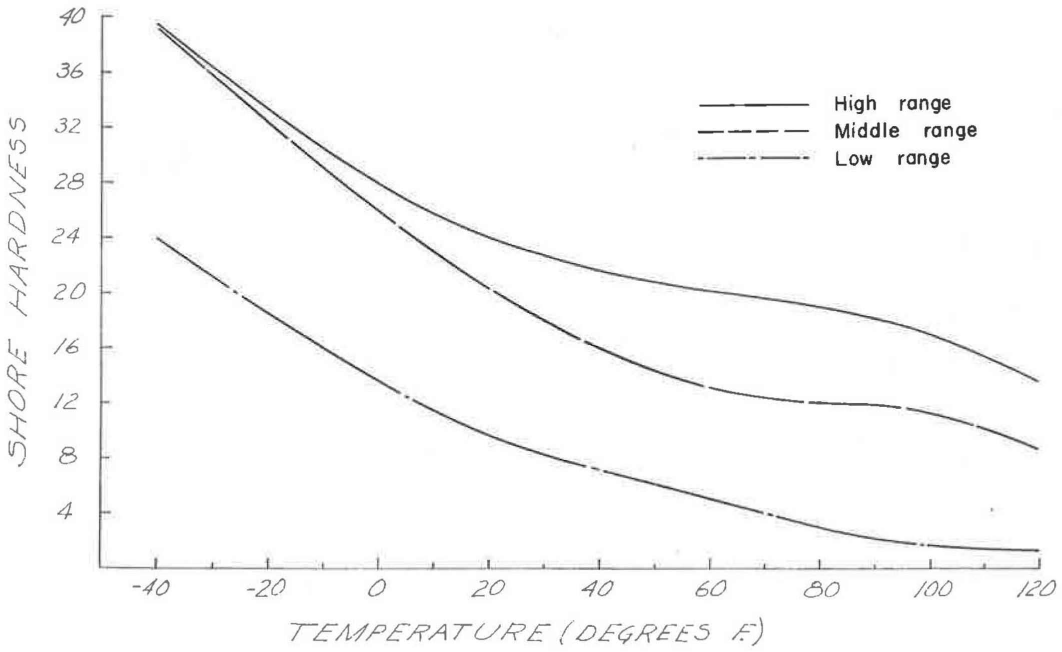

Figure 34. Shore hardness vs temperature.

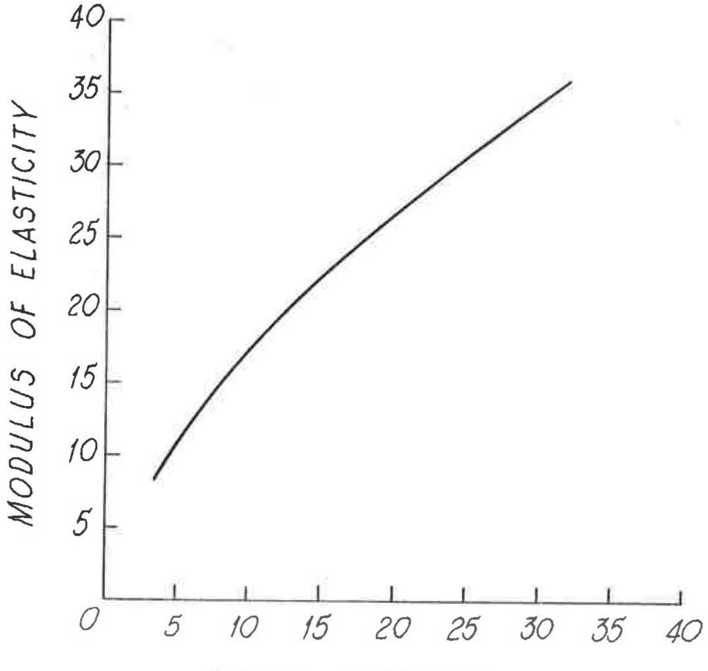

Figure 35. Tensile modulus vs Shore hardness.

Appendix B

SOLUTION OF SAMPLE PROBLEMS

Sealant as an Elastic Material

To cover the range of field conditions, three cases of stress should be considered: (a) tension (or compression) alone, (b) tension plus shear, and (c) compression plus shear. For purposes of illustration, dimensions of a typical highway bridge are used. The structure is a 60-ft span rolled-beam bridge with a concrete deck. The beams are 33WF130 spaced at 6 ft cc. The joint sealant is a square cross-section, 1 in. wide by 1 in. deep.

Tension Alone.—Assume the sealant material is placed at 75 F. Temperature range is -40 to +120 F, maximum differential is 75 - (-40) = 115, and coefficient of expansion of bridge is 0.0000065 (steel). Anticipated movement = 0.0000065 × 60 × 115 × 12 = 0.54 in. due to temperature.

Tension Plus Shear.—The case of tension plus shear could be caused in two ways, first by the impact of a truck wheel bearing on the extreme end of the bridge, or rotation at the support as caused by midspan deflection. A truck wheel bearing on the extreme end of the bridge tends to deflect the short cantilevered portion of the bridge which extends beyond the centerline of bearing (assumed to be 1 ft). For a 20-ton truck, one rear wheel = W(0.4) = 0.4 × 20 × 2 = 16 kips, distribution factor (AASHO) = S/5.5 = 6.0/5.5 = 1.09. Impact at 30 percent is given by P = 16 × 1.09 × 1.3 = 22.7 kips. Assume this load is concentrated at the end of the short cantilever; therefore,

$$\text{Deflection} = \frac{PL^3}{3\,EI} = \frac{22.7 \times (1)^3 \times 1728}{3 \times 29 \times 10^3 \times 6700} = 0.000067 \text{ in.}$$

This deflection represents a shear-type movement in the sealant but its magnitude is only one-ten thousandth of the movement in the tensile direction; therefore, shear can be neglected. To consider the end rotation of the structure, consider the 20-ton truck at midspan, using the same distribution factor and impact. Therefore, P = 20 × 1.09 × 1.3 = 28.4 kips, and end rotation θ is given by:

$$\theta = \frac{PL^2}{16\,EI} = \frac{28.4 \times 60^2 \times 144}{16 \times 29 \times 10^3 \times 6700} = 0.0047 \text{ rad}$$

Movement at top of slab = 45 × 0.0047 = 0.213 in.; top Wx = length at top of extended sealant = 1.54 + 0.213 = 1.753 in. For the amount of rotation shown (0.0047 rad), the upward movement at the end of the slab will be 0.060 in. This is a shear-type movement but it is only $^{8}/_{100}$ of the movement in the tensile direction and makes virtually no change in the stress magnitude.

The implication of these computations is that shear may, in general, be neglected in combination with tension, but that the case of end rotation is important. However, this importance comes, not from shear, but from the fact that it causes a further extension of the sealer in the tensile direction, which in this case is almost one-half as much (0.213 vs 0.54) as the extension caused by temperature change. This fact should be given careful consideration in the future design of the service life of any joint sealer.

Using the statistical approach, the stresses in the sealant are determined as follows:

Total extension = 0.54 + 0.213 = 0.753 in.
Joint width = 1.0 + 0.753 = 1.753
$\lambda_1 = \lambda = 1.753/1.0 = 1.753$
$\lambda_2 = 1/\lambda = 1/1.753 = 0.570$
$\lambda_3 = 1$
$W = \frac{1}{2} G \left[\lambda^2 = 1/\lambda^2 + 1 - 3\right]$

The only force acting is in the tensile direction; therefore,

$$f = \frac{dw}{d\lambda} = G\left[\lambda - \frac{1}{\lambda^3}\right]$$

The value of G (34 psi) is in the value for a high modulus tread stock rubber which is as hard a material as could be practicably used as a sealant:

$$f = 34\left[1.753 - \frac{1}{(1.753)^3}\right] = \left[1.753 - 0.185\right] 34 = 53.3 \text{ psi}$$

This force f is the magnitude of the force acting on a unit cross-sectional area in the unstrained state. For this specific problem it is acting adjacent to the bonding surface where no neckdown has taken place. This value at the interface must be related to the peel strength of the material in question. The polysulfides show a peel strength which averages only 42 psi by test, so that a peel failure seems imminent. The stress "t" on the necked-down cross-section of the sealant is given by:

$$t_1 = \lambda_1 f_1 = 1.753 f_1 = 93.5 \text{ psi}$$

Comparison of this value with the true stress-true strain curve indicates that a polysulfide will stand stresses of three times this magnitude at this strain before failure. In brief, cohesion looks safe but a peel failure seems imminent.

Compression Plus Shear.—Separate from, but related to, these examples is the case at the other end of the temperature scale. When the bridge is fully expanded and the sealer is compressed, the latter extrudes above the roadway surface. At this time, temperature is high and the sealant has softened somewhat. Experience shows that these conditions normally result in failure by folding and flattening of the sealant under the action of traffic. However, since we are working under the assumption that the sealant is fully elastic, the net effect of traffic will be the depression of the sealant back into the joint. The stress in the sealant at this time will be the resultant of a compressive stress caused by temperature and a punching type of shear as caused by the wheel load. Movement due to compression = (1.20 - 75) × 0.0000065 × 60 × 1.2 = 0.21 in. due to temperature;

$$\lambda_1 = \frac{1 - 0.21}{1.0} = 0.79$$

$$f = \frac{dw}{d\lambda} = G\left[\lambda - \frac{1}{\lambda^3}\right] = 34\left[0.79 - \frac{1}{(0.79)^3}\right] = 42.5 \text{ psi}$$

The amount of shear is determined by writing and differentiating the parabolic equation of the extruded sealant. For this case shear is the downward movement back into the joint of a differential element of sealant adjacent to the interface. It is expressed as the tangent of the angle ϕ which the sealant makes with the pavement: $\alpha = \tan \phi = 0.47$ and shearing stress $\gamma = G\,\alpha = 34\,(0.47) = 15.9$ psi. Combining the direct compression stress with the shearing stress gives a principal stress, S max = 47.7 psi. This stress, which because of the nature of the loading is related to peel strength, also exceeds the peel strength of the polysulfides.

Sealant as a Flowing Solid

The illustrative problems use the following equivalent model equations (model shown in Fig. 10):

$$G_1{}^A = G_1{}^B + G_2{}^B \tag{9}$$

$$G_2{}^A = \frac{G_1{}^B G_2{}^B \left(\eta_1{}^B + \eta_2{}^B\right)^2 \left(G_1{}^B + G_2{}^B\right)}{\left(\eta_1{}^B G_2{}^B - \eta_2{}^B G_1{}^B\right)^2} \tag{10}$$

$$\eta_2{}^A = \eta_1{}^B \eta_2{}^B \frac{\left(G_1{}^B = G_2{}^B\right)\left(\eta_1{}^B + \eta_2{}^B\right)}{\left(\eta_1{}^B G_2{}^B - \eta_2{}^B G_1{}^B\right)^2} \tag{11}$$

$$\eta_3{}^A = \eta_1{}^B + \eta_2{}^B \tag{12}$$

The data for these problems were taken from the creep and stress relaxation curves included here for the medium range material (Shore A = 12). The strain rate is taken from a curve of joint movement with temperature change. Hourly fluctuations of temperature were obtained from the U. S. Weather Bureau. The temperature curves are plotted for the one day in March which showed the greatest temperature variation. According to this curve, the rate of temperature change and, consequently, the strain rate remain relatively constant for a period at 0.0014 in./in./min.

The following data were taken from the creep curve for Model A:

$$G_1{}^A + \frac{1}{3} E_1{}^A = 10 \text{ psi}$$

$$G_2{}^A = \frac{1}{3} E_2{}^A = 7 \text{ psi}$$

$$\eta_2{}^A = 960 \text{ lb-min/sq in.}$$

$$\eta_3{}^A = 9,600 \text{ lb-min/sq in.}$$

From the equivalency relations, the constants for Model B are

$$G_1{}^B = 7.0 \text{ psi}$$

$$G_2{}^B = 3.0 \text{ psi}$$

$$\eta_1{}^B = 9,300 \text{ lb-min/sq in.}$$

$$\eta_2{}^B = 300 \text{ lb-min/sq in.}$$

$$\tau_1 = \frac{\eta_1}{G_1} = 1,330 \text{ min}$$

$$\tau_2 = \frac{\eta_2}{G_2} = 100 \text{ min}$$

Since a bridge will normally build up stress until it lurches in a sudden movement, this amount of movement will have to be assumed. This amount of lurch (ϵ_0) assumed is 0.25 in., slightly more than half the anticipated movement in a day's time.

Case I.—Where $\epsilon = \epsilon_0 + \beta t$, determine the stress at t = 60 min after an initial lurch of 0.25 in.

$$\sigma = \left[\beta\eta_1 + \exp - t/\tau_1 (G_1 \epsilon_0 - \beta\eta_1)\right] + \left[\beta\eta_2 + \exp - t/\tau_2 (G_2 \epsilon_0 - \beta\eta_2)\right]$$

$$= \left[0.0014\,(9300) + e^{-0.066}\,(7.0 \times 0.25 - 0.0014 \times 9300)\right] + \left[0.0014\,(300) + e^{-0.60}\,(3.0 \times 0.25 - 0.0014 \times 300)\right]$$

$$= 13.02 + -11.6 + 0.42 + 0.18 = 1.92 \text{ psi}$$

Case II.—In the event that the bridge does move ideally, $\epsilon_0 = 0$. The stress at t = 60 min reduces to

$$\sigma = \left[\beta\eta_1\,(1 - e^{-t/\tau_1})\right] + \left[\beta\eta_2\,(1 - e^{-t/\tau_2})\right]$$

$$= 13.02\,(1 - e^{-0.066}) + 0.42\,(1 - e^{-0.60}) \cong 0$$

Case III.--In the event that the bridge moves through an initial lurch and then remains at a constant elongation, $\beta = 0$ $\epsilon_0 = 0.25$ and t = 60 min:

$$\sigma = \left[G_1\,\epsilon_0\,e^{-t/\tau_1}\right] + \left[G_2\,\epsilon_0\,e^{-t/\tau_2}\right]$$

$$= \left[7.0 \times 0.25 \times e^{-0.066}\right] + \left[3.0 \times 0.25 \times e^{-0.60}\right]$$

$$= 1.80 + 0.41 = 2.21 \text{ psi.}$$

It becomes immediately apparent that when stress relaxation enters the picture, the entire outlook changes. The stresses shown here are well below the demonstrated peel strength of the polysulfides; therefore, under normal conditions, the sealant should not fail.

Bridge Joint Sealing—Its Materials and Mechanical Problems

H. B. BRITTON
New York State Department of Public Works

An extensive search for materials to seal joints in structures was undertaken in 1952. Materials investigated included hot poured or extruded rubberized asphalt, silicone rubbers, liquid neoprene, asphalt emulsion, urethane, latex and a nonmeltable mastic. Materials formulated with liquid polysulfide polymers appeared to have the physical characteristics required for effectively sealing joints in structures. Shore A hardness limits were derived from determining a workable material at -20 F. The physical properties of the material required should be as follows: (a) Shore A durometer at 77 F of 10-15; (b) not flow at high temperatures; (c) retain flexibility and have extensibility at -20 F of at least 100 percent; (d) be capable of effecting chemical or mechanical bond at a temperature of approximately 40 F; (e) cure rapidly; and (f) be thixotropic and have the ability to withstand invasion of foreign particles.

Field test installations indicated a definite relationship between the depth and width of material placed. In structures where a depth of material was approximately one-half the width of the joint opening, the sealant performed much more satisfactorily than when the depth of material equaled or exceeded its width.

Some reasons for failure of materials are outlined; the areas of responsibility with regard to obtaining properly sealed joints are listed.

•WHEN TWO-LANE highways were the ultimate in the network of roads, sealing of joints in structures was looked on as a necessary evil and received little, if any, attention or inspection. It was not until the advent of the limited-access highway and the extensive use of elevated structures in metropolitan areas that the necessity of adequately sealing bridge joints was fully realized. Just as no one person or segment of this industry is at fault for this condition, no one person or segment is responsible for the progress that has been made toward its solution. There has been considerable effort extended by a few who have contributed much to a better understanding of the problems involved, both with regard to material requirements and joint geometrics and construction.

An analogy might be drawn between the roof of the covered bridge of the past and the bridge joint sealers of the present. The roof or covering of a bridge of a century or more ago was the means employed to protect the structural components from the assault of the elements. Today the modern counterpart of this roof is the lowly, but none the less important, joint sealer. It is on this joint sealer that we must rely for complete sealing in structural decks and wearing surfaces, thereby protecting such vital members as bearings, structural steel, and supporting concrete from the onslaught of deleterious solutions.

It is safe to conjecture that before 1957 not more than 50 lines were devoted to the subject of joint sealing in any set of state specifications. Up to this time, joint sealers

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were not an item of the contract. In most instances the cost of sealing joints, which included all labor and materials charges, were contained in the price bid for the various concrete items in the contract.

In 1952, New York State began an intensive search for materials that would conceivably seal the expansion and contraction joints required in normal bridge construction. The first material that appeared to have possibilities was a rubberized asphalt joint sealing compound. This material was a hot-poured or extruded type conforming to the requirements of Federal Specifications SS-F-336a. The samples submitted were laboratory produced and consisted of two 2- by 2- by 2-in. concrete blocks bonded together with ¾ in. of sealing material. These samples were not subjected to any standard test procedures, nor were duplications of the samples produced by our personnel. After much handling and inspection of these samples, the material was adopted by the Department and specified for use on structures. Under construction conditions this material failed to produce the desired results in that it failed to adhere to the interface of the joint. In fact, some in its extruded form was placed in the joint without removing the protective shipping film.

By 1954 there was a marked increase in the number and type of sealants being submitted to the Department for approval. The then Deputy Chief Engineer, C. F. Blanchard, directed that no materials would be approved without qualified tests being made. With our limited knowledge or perhaps our superb ignorance, it was decided to test all new materials under actual construction conditions.

At this time, the New York State Thruway was nearing completion and all structural joint sealing failures had to be repaired. Joseph W. LaFleur, the Bridge Maintenance Supervisor, selected one bridge carrying the Thruway on which experiments were made with a number of joint sealers. Because the bridge maintenance crew was well trained and equipped, joint areas could be properly prepared in compliance with the knowledge then available, which was that the sidewalls or interfaces of the joint must be sound and clean.

All sealers selected for test on this structure were of the cold-pour variety. Test installations were made of two silicone rubbers, one liquid neoprene, one asphalt emulsion, one urethane, one latex, and one nonmeltable mastic which is a blend of refined asphalts, resins and plasticizing compounds, reinforced with long-fiber asbestos.

One silicone rubber employing a liquid accelerator or catalyst failed in less than a month. The failure was both in adhesion and cohesion. A considerable loss in volume was evident which can be expected when volatile liquids form a considerable part of the mixture. The neoprene failed in cohesion, perhaps because the material contained only 60 percent solids and the volume loss exhibited was considerable. The asphalt emulsion failed for the same reason. The urethane and latex disintegrated within a month. One silicone rubber and the nonmeltable mastic produced an effective seal until they were removed approximately two years later.

All materials were placed by representatives of the companies involved in full compliance with their recommendations. There were disadvantages in all these products in that none but the mastic was thixotropic. All were difficult to place and most required a primer which had to be applied to the interface of the joint anywhere from ½ to 4 hr before application of the joint sealer.

By late 1955, little progress had been made in effectively sealing structural joints but we had made some important contacts with technical representatives of sealer manufacturers who were willing to give of their time and materials to aid in the attempt to solve the problems.

By the spring of 1956, much technical data and boxes of samples, both preformed and liquid, had been accumulated. The prefabricated samples were evaluated in an improvised laboratory. It was important that physical characteristics of these materials be studied in relation to the structural and climatic conditions to which they would be subjected. At this time only extensibility and the adhesive and cohesion properties of joint sealers were considered. Preformed samples were tested in a jig adapted for use on a machinist's vise. All preformed samples were still of 2- by 2-in. concrete block bonded with from ¾ to 1 in. of joint sealer. The samples were subjected to temperatures ranging from -20 to 350 F and to extension and rotation tests at -20 F. They were also immersed in salt solution, gasoline, kerosene, alcohol and permanent antifreeze.

Materials tested were four liquid polysulfide polymers, four polysulfide polymers extended with coal tar, one latex rubber, and one silicone rubber. Test samples were produced from the bulk material supplied by the various producers and were subjected to the same series of tests that were applied to the preformed samples.

At this time, it became apparent that some relationship should be established between the hardness of the cured sealer and the temperature range within which it could be expected to function. Working with a low temperature limit of -20 F, it was determined that a Shore A durometer of 40 is the upper limit at which these materials would retain the desired elastic properties. It was determined through trial and error that at 77 F the sealer must have a Shore A durometer of 10 to 15.

By the spring of 1956 three materials showed definite promise: (a) one liquid polysulfide polymer, (b) one liquid polysulfide polymer extended with coal tar, and (c) one silicone rubber.

These joint sealers were next placed in the transverse expansion and construction joints of three already constructed bridges. It was felt that if this type of joint could be successfully sealed, there would be no difficulty in sealing longitudinal joints.

Existing material was removed from the joint areas and the interfaces were prepared to accommodate the new joint sealing material. The first attempt at cleaning the interface of the joints was made by power-driven wire brushes, but this proved unsuccessful and sandblasting had to be used. The joint area was then blown clean of all extraneous materials.

On June 5, 1956, the liquid polysulfide polymer extended with coal tar was installed. This material was a two-component 1:1 mix, thixotropic in nature, requiring no primers, and exhibiting skin or surface cure in approximately 15 min at 75 F. Application was accomplished by a machine developed by the formulators of the material. This equipment was not completely satisfactory because the metering pumps did not provide a continuous positive supply of the two-components to the mixing chamber located 6 or 8 in. from the nozzle from which the sealant was extruded. The equipment was capable of applying the joint sealer at a rate of approximately 10 ft/min.

The four joints tested were from 1¼ to 1½ in. in width and ½ to ¾ in. in depth. The structure is on a 40° skew and the length of each joint was approximately 60 ft. All appearances that day indicated that we were approaching the solution to the sealing problem.

The next day, the equipment was used to place this same type of sealing material in the joints of a Thruway structure. Faulting of the equipment caused delivery of improperly proportioned material to the mixing chamber with the result that the sealant failed to cure properly, thus failing to produce the desired product. Corrections and adjustments were made to the equipment and the sealing of the joints progressed in a satisfactory manner. The transverse joints on this square structure were approximately 45 ft long and ranged from 1 to 1¼ in. in width and ¾ to 1 in. in depth.

On July 10 and 11, the liquid polysulfide polymer was installed. This was a two-component 1:10 mix, available in two grades, one for horizontal joints and a heavy type for vertical joints. It required that a primer be applied to dry concrete interfaces and allowed to air dry. Surface cure time at 75 F was approximately 4 hr. The structure was square with joints approximately 72 ft long and ranging from 1½ to 2½ in. in width and 1½ to 2 in. in depth. The material was hand mixed in ¾-gal kits and poured directly from the container into the joint.

On July 12 and 13, the silicone rubber joint sealer was installed. This material was a 3:1 mix requiring a primer and exhibiting skin or surface cure in approximately 2 hr at 75 F. Because of flow characteristics, it could only be used in horizontal joints. We attempted to use this material in the vertical joints by providing a bulkhead but the results obtained were very unsatisfactory. The joints in this square structure were in very poor condition due to the spalled faces. Some joints were as much as 4 in. wide and the average depth was 2 in.; the length was approximately 36 ft. The material was again hand mixed in ¾-gal kits and poured directly from the container into the joint.

The material in these three test installations failed or showed signs of failure in less than 2 mo. We had, however, gathered considerable information on the physical and chemical characteristics of the materials employed and some on the behavior pattern of these sealants with regard to their dimensions within the joint.

The 40 Shore A durometer hardness of these materials at 75 F was definitely too high. Either the sealing material or the primers were not compatible with the premolded bituminous joint material already in place in the structures. There appeared to be a definite relationship between the depth and width of material that would effectively produce a properly workable sealed joint. This has since become known as the shape factor. On the structure where the liquid polysulfide polymer extended with coal tar was placed, the depth of material was approximately one-half the width of the joint opening and the sealant performed much more satisfactorily than on those structures where the depth of material equaled or exceeded its width.

For reasons of economics it was decided to concentrate on the liquid polysulfide and the liquid polysulfide polymer extended with coal tar. As a result of many conferences it was decided that the material used in New York State should have a Shore A durometer hardness at 77 F of 10 to 15, not flow at high temperatures, retain its flexibility, have an extensibility at -20 F of at least 100 percent, be capable of effecting chemical or mechanical bond at approximately 40 F, cure rapidly, be thixotropic, and have the ability to withstand invasion of foreign particles.

With the aid of two manufacturers, by the winter of 1956 to 1957, after the expenditure of several hundred thousand dollars in research, development and engineering of equipment, it appeared that materials could be produced effectively to seal expansion and construction joints in bridges.

In June 1957, the joint areas of the two structures sealed with liquid polysulfide polymer, alone and extended with coal tar, were again prepared for resealing with the same materials. With the experience gained previously, these applications proved far more successful. With these exhibited improvements, it appeared reasonable to utilize these materials with a full understanding that there would be improvements made in the sealants and method of application. It is a basic economic fact that further research and development of these materials would be accelerated if the manufacturer could realize a return on their initial investment. The benefits of these improvements would then accrue to the user.

In 1957, New York State issued special specifications for the use of these materials for sealing bridge joints. One significant difference from previous practice was that sealing of joints was made an item of the contract and paid for accordingly.

There was still a lot to be learned. It was soon realized that not only the ratio of depth to width was important but also a bond-breaker was required at the bottom of the sealant to eliminate or reduce any restraint to free movement. This resulted in the use of wax-backed or polyethylene tapes at the bottom of the joint areas to be sealed. Later we learned that extensibility was not the only requirement in a joint sealer. Since time of construction, the contractor's schedule of operation, and temperature could dictate the time at which the joint would be sealed, compression could be the controlling factor. With this in mind, joint details were revised and a layer of upholsterer's piping cord, later revised to utilize a flexible urethane foam, was required between the premolded joint material and the polysulfide sealant. Premolded bituminous joint material was replaced by self-expanding cork.

Failures were still prevalent. The reasons were many and could be attributed to poor joint design, or construction, apathy with regard to inspection, ignorance or misunderstanding of preparation of joint surfaces and mixing and applying of the sealer, or a total disregard of the specifications for an item of the contract. Some typical examples point up the preceding comments:

1. A steel expansion dam was designed with a width of 1¼ in. providing a sealable joint interface of ⅝ in. These dams as constructed and ready for sealing had a width of from 3 to 4 in.
2. Joints detailed as 1 in. with a joint interface of ½ in. when constructed and ready for sealing were 1 in. in width and the preformed joint filler was so positioned that only ⅛ in. of joint interface was available to receive the sealer.
3. Joints were sealed without supervision or inspection in the rain with mud present in the joint area.
4. Two-component materials which required machine mixing and placing were measured out in separate cans and poured into the joint opening.

5. On one job, the crew did not even bother to put the A and B components into the same joint. Instead, they used up each component separately.

6. Maintenance personnel, not recognizing the new materials, did their usual good job, pouring hot tar on top of the sealants. On cooling, a rigid material was left in contact with the upper face of the sealant, restraining the movement in the extreme fibers, thereby contributing to their failure.

During the past 6 years the sealant manufacturers have been most coöperative. They have studied the problems and have attempted to produce the material required to seal properly designed and prepared joints.

Sealant materials other than those based on the polysulfide polymer have been formulated in the past 2 or 3 years with the hope that they might solve the problem. Three joint sealers in particular have been subjected to limited test applications: a two-component flexibilized epoxy, a two-component urethane rubber, and a premolded neoprene.

The flexibilized epoxy material showed considerable possibility. It performed satisfactorily with regard to adhesion and cohesion, expansion and compression. Temperature change had only a slight effect on the hardness of the cured material. The differential in Shore A hardness of this material was only eight points in 95 degrees of temperature change, indicating that a Shore A durometer of 30 at 75 F could be effectively employed. The formulators of this material, however, withdrew it from the market when they encountered difficulty in reproducibility from batch to batch. The urethane rubber joint sealer has not been given sufficient chance to demonstrate its capabilities.

The premolded neoprene joint sealer was placed on October 26, 1963. The joint as designed and detailed calls for a width of $\frac{3}{4}$ in. and a depth of $2\frac{1}{2}$ in.; as constructed, it was 1 in. wide and $2\frac{11}{16}$ in. deep. The top of the joint area had been given a $\frac{1}{2}$-in. radius tooled finish. This type of joint filler is designed to function under conditions of compression only. The material supplied was 2 in. wide by 2 in. deep and, when compressed to meet the requirements of 1 in. width of joint, had a depth of $2\frac{1}{2}$ in. Portions of the preformed cork joint filler and of the structural slab had to be removed to provide sufficient depth for the placement of the compressed material. The concrete interfaces were poorly constructed in that honeycombing was evident approximately 1 in. below the top surface. This material is not designed to and cannot seal a concrete joint interface that exhibits spalling.

In recognition of the experience gained to date, the HRB Subcommittee on Joint Sawing-Sealing in Overlays has, after several meetings during the past two years, attempted to assess the areas of responsibility with regard to obtaining properly sealed joints as follows:

1. Engineer (Design).—Design and detail expansion and construction joints giving full recognition to the shape factor requirements of the material to be used, indicating the limits of anticipated movement, together with a possible indication of the desirable joint confirmation with relation to time for sealing.

2. Engineer (Construction).—Supervise the construction of expansion and construction joint areas to insure their compliance with the Design Engineer's requirements as it relates to time and temperature. Supervise and inspect the preparation of joint areas together with the preparation, mixing and placing of the joint sealant in full compliance with the specifications and manufacturer's recommendations.

3. Contractor (or Subcontractor).—Construct joints as designed and detailed in full compliance with contract requirements. Guarantee the employment of only qualified personnel to insure the proper preparation of the joint areas as well as the preparation, mixing and placing of the sealant in full compliance with the requirements of the specification and the sealant manufacturer's recommendations.

4. Sealant Manufacturer.—Formulate quality-controlled materials capable of sealing properly designed joints indicated on the contract plans. Recognition should be given to the time needed for fully curing the material as well as the required functioning of the joint with relation to the structure. Complete recommendations should accompany each unit of material, outlining procedure to be followed with regard to preparation of the joint interface surfaces as well as the proportioning, mixing and placing of the

sealant. The manufacturer should be familiar with the conditions of bridge construction and should provide technical assistance to the sealing applicator who inspects the joint areas before sealing. Should the joints, as produced, or the surface preparation be in violation of the design, construction or specification requirements, the manufacturer should refuse to supply any materials, if in his opinion, these violations will preclude a successful application.

A recent investigation conducted by California has added some very interesting information relative to observed sealing failure. Failures were occurring at the approach side of the leading edge of spans only. Observation under normal traffic indicated a positive jump of the deck in the direction of traffic. This phenomenon is attributed to the impact forces imposed by high-speed truck traffic on initial contact with the deck surface.

Corrective measures included closed cell neoprene sheet cut to conform to the joint dimensions, leaving room for the joint sealant at the top surface. The neoprene sheet was cemented to one interface only. On completion of cure of the adhesive, a barrier strip of pressure-sensitive polyethylene tape was placed over the upper face of the neoprene sheet and the sealing of the joint was completed using a liquid polysulfide polymer extended with coal tar. This type of investigation and approach to a solution constitutes a significant contribution to the solving of a most troublesome problem.

Some recent experimental work carried on by John P. Cook at Rensselaer Polytechnic Institute has produced some much needed data regarding the behavior of these materials. His findings indicate that further research in the development of elastomeric sealants would be to the advantage of all concerned with this problem.

ACKNOWLEDGMENTS

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New York State Experience with Concrete Pavement Joint Sealers

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The primary method of evaluating sealer performance at test sites in New York State has been to make frequent periodic observations with a special effort to observe the sealers during subzero temperatures. In a test area established in 1963, time-lapse movie photography is being employed to obtain visual records of sealer performance.

Observations of joint sealing materials installed during 1959 indicate that extruded neoprene has given excellent service. However, the appropriate width tubing must be installed without stretching in joints of a consistent and predictable width. Thiokol with extenders performed well for approximately 18 months when cracks began to appear over air bubbles formed during installation and some adhesion failures developed. Polysulfide with tar extenders gave excellent service for 1 year, after which surface cracks appeared and progressed through the material. The ability of hot-poured rubber asphalt to seal joints varied, depending on the season installed. Materials placed during hot summer weather failed in less than 4 months; material poured in the fall performed well for about 1 year, when adhesion failures developed. Rubber asphalt, cold-poured with solvent, gave very poor performance and failed entirely within 4 months. Observations on polyurethane with tar extenders and other recently developed sealers are continuing.

•TRANSVERSE JOINTS in concrete pavement are constructed to prevent random cracking due to stresses caused by the contraction of the concrete. These joints, if left unsealed, afford an excellent collection point for water and incompressible materials. Water running through the joints can cause corrosion of the load-transfer devices, weaken the subgrade and possibly cause pumping. Incompressible materials in the joint create localized stresses in the concrete when the joint attempts to close; these stresses usually result in spalling. To prevent such occurrences, a sealer is placed in the joint.

The difficulty of maintaining a sealed joint is primarily caused by the opening and closing of the joint. Ideally, to perform its intended function, a joint sealer must remain in contact with the joint face as the joint opens and closes. The sealer material should remain pliable and resilient at all temperatures which might be encountered; it should become neither excessively soft during hot weather nor hard and brittle during cold weather. If a sealer softens appreciably at high temperatures, it is susceptible to the intrusion of foreign material and may sag deeper into the joint or be tracked out onto the pavement by the action of traffic. At low temperatures, the sealer must be ductile

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enough to withstand elongation and flexure without separating from the joint face or tearing internally.

As early as 1910, asphalt and pitch were used to seal joints in concrete pavements. However, continued use of these materials showed their inadequateness. Attempts were made by some states to modify the asphalt by adding a mineral or diatomaceous earth filler. However, little if any improvement was observed. Until 1958 the New York State Department of Public Works specified a 50-60 penetration grade asphalt cement to seal joints in concrete pavements. However, in hot weather the sealer became soft, was incapable of resisting penetration by foreign material, and was often tracked onto the pavement. In cold weather it became brittle and cracked, permitting the infiltration of water and foreign materials.

INVESTIGATION

Recognizing this problem, Deputy Chief Engineer B. A. Lefeve with the cooperation and support of the district engineers arranged for experimental installations of new sealers as they became available. This work was started about 1955 and when the Bureau of Physical Research was formed in 1958 a project dealing with joint seal materials was initiated. Locations of all previous and current field experiments were recorded and an attempt at a uniform observation survey was made. However, it soon became apparent that these materials were very difficult to compare because of the different ages and preparation of the joints, and it was decided to establish a field test where different types of sealers would be placed at the same time under the same conditions.

A field test area was established on I-87 just north of Albany. The six types of sealers under test in this area can be described as: (a) rubber asphalt, cold-poured, with solvent; (b) rubber asphalt, hot-poured; (c) latex with extenders, premixed, cold-poured; (d) polysulfide tar (Thiokol), nozzle-mixed, cold-poured; (e) polysulfide tar, hand-mixed, cold-poured; and (f) polysulfide with extenders, premixed, cold-poured. These materials were placed in transverse contraction joints spaced at 60 ft 10 in. All joints were hand formed and measured about $^{3}/_{4}$ in. wide at the pavement surface when sealed. The joints were cleaned with a power wire brush and then blown out with compressed air. A styrofoam filler was placed in the lower portion of the joint and the sealers were installed by manufacturers' representatives using their own equipment.

Observations and measurements of the joints were conducted approximately every 3 months for 2 years. The air temperature, determined during each observation, varied from 90 to 5 F. As a result of these temperature variations, the maximum change in width of all test joints was found to be approximately the same, amounting to an annual movement of about $^{1}/_{4}$ in . during this particular 2-year period.

In the fall of 1960, Mr. Lefeve arranged for two test installations of a new preformed neoprene sealer, one on Fuller Road in Albany and the other on the Sunrise Highway near Babylon, Long Island. He then asked the Bureau of Physical Research to observe these seals. The experimental installations and observation of this type of material in contraction joints spaced at 60 ft 10 in. continued during 1961.

Installation of the neoprene sealer is accomplished by first coating the joint faces with a lubricant adhesive and then forcing the tubing into the joint. When first placed experimentally, this type of sealer was inserted with putty knives and screwdrivers. At present, a flanged roller is usually used as shown in Figure 1.

Neoprene and urethane tapes were also installed experimentally near Albany during the fall of 1962. This material was $1^{1}/_{2}$ and $2^{1}/_{2}$ in. wide and 0.040 and 0.050 in. thick, respectively. The tape was fastened with epoxy resin to the surface of the concrete on either side of the joint. To minimize damage to the tape, the pavement surface near the joint was ground down to a depth of 0.060 in. on 17 of the 19 experimental joints. Curing of the epoxy resin was extremely difficult since the air temperature was near 40 F and the weather was windy, cloudy and damp. These conditions necessitated heating the joint during the installation.

Development of new sealers during the early 1960's prompted a new field test in 1963. Manufacturers of joint sealers who expressed an interest in a field test were

Figure 1. Installing preformed neoprene sealer.

invited to install their products in a new concrete pavement on the Delmar Bypass south of Albany. In this field test, 21 companies installed 37 products, representing nine different categories of sealers: (a) polysulfide with extenders; (b) polysulfide tar; (c) polyurethane foam impregnated with asphalt; (d) polyurethane with extenders; (e) rubber asphalt, cold-poured, with solvent; (f) rubber asphalt, hot-poured; (g) neoprene, preformed; (h) latex with extenders; and (i) adduct rubber. All sealers were placed in transverse contraction joints formed with $^3/_8$-in. wide plastic inserts. These joints were spaced at 60 ft 10 in. Before sealing, the joint faces were etched with a 20 percent solution of hydrochloric acid and the residue was flushed out with clean water. It was requested that the participating companies place a filler in the lower portion of the joint groove which would be compatible with their sealer. Most commonly used fillers were polyurethane foam strips and butyl rod stock, although a few companies elected to use upholsterers' cord and jute rope. Each product was installed in five joints by the manufacturers' representative after the filler was placed and the concrete had thoroughly dried.

Time-lapse movies of the pavement joints are being used to evaluated the performance of the sealers. For this purpose, a 16-mm magazine-loading movie camera is mounted on a wooden jig. The jig is positioned in the same location for each exposure by aligning two sets of guide wires directly above a pair of brass pins set in the concrete (Fig. 2). A film magazine for each joint to be photographed is exposed for 2 seconds every other week. The film when projected will show an accelerated movie of the life of the sealer.

RESULTS AND DISCUSSION

Observations of the liquid joint sealers revealed three typical failures: adhesion, cohesion and extrusion. Figure 3 shows adhesion failure which occurs when the tensile stress in the sealer exceeds the bonding force available at the joint face. The tearing of the sealer in Figure 4 illustrates cohesion failure which occurs when the bonding force at the joint face is greater than the sealer tensile strength. An extruded joint sealer is shown in Figure 5. The sealer is forced from the joint when the joint closes to a point where there is not enough volume to contain it. The extrusion is aggravated when depressions in the sealer become filled with incompressible material. This action can progressively entrap sand and small stones until the joint is nearly filled.

The rubber-asphalt, cold-poured with solvent type of sealer solidifies by the evaporation of the solvent. Initially, it is easily "tracked" onto the pavement and is capable of absorbing large quantities of sand and stones. A condition survey, 4 months after installation, indicated practically 100 percent failure in adhesion or cohesion. Many stones had penetrated the surface of the sealer and in some instances, pieces of the sealer were missing. In cold weather, the sealer became extremely hard and brittle.

The rubber-asphalt, hot-poured sealers gave variable performance in the test areas, depending on the season installed. The material poured during hot summer weather failed in less than 4 months, whereas that poured in the fall performed satisfactorily for an average of approximately 1 year at which time adhesion failures developed. During hot weather the material was soft and where extruded was easily smeared on

Figure 2. Time-lapse movie camera.

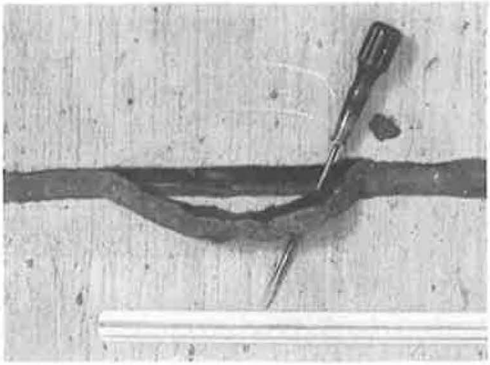

Figure 3. Adhesion failure.

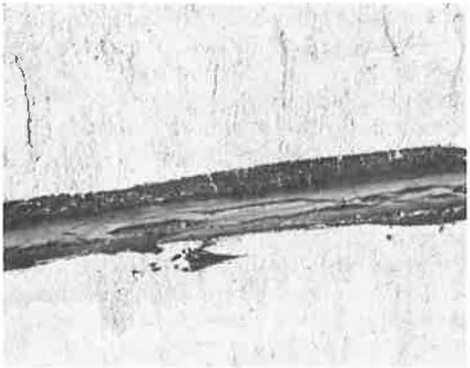

Figure 4. Cohesion failure.

Figure 5. Extruded sealer.

the pavement. Stones and sand were easily pressed into the sealer in this condition and in cold weather the sealer became hard, usually failing in adhesion.

The latex with extenders was the consistency of caulking compound when installed and appeared to form an effective seal for approximately 5 months. However, during the winter the surface of the sealer hardened and became checked with small shallow cracks. On close examination it proved to be saturated with water. Although little adhesion failure was apparent after 12 months, it was easy to either puncture the sealer or pull it from the concrete. The ease with which the sealer could be displaced seems to leave its effectiveness as a joint sealer open to question. After 18 months, this material hardened and failed in adhesion.

All polysulfide-tar sealers were cold-poured; the two components were either combined by hand mixing or in a nozzle-mixing machine. Some difficulty was encountered with the proportioning pumps. Mechanically driven pumps proportioned the components more satisfactorily than those driven by compressed air. Unfortunately, since both components are black and essentially the same consistency, it is difficult visually to detect an improperly proportioned mixture until it fails to cure. Polysulfide tar gave excellent performance for about 1 year. As it aged, the surface became cracked. These cracks progressed until they extended completely through the material.

The polysulfides with extenders are two-component sealers which are pre-mixed and then placed in the joint without heating. Judging from the bubbles that form in the material, air is easily entrapped during installation or the curing reaction releases a gas.

As long as these bubbles remain intact they pose no problem; however, when they become punctured, they afford an excellent pocket for the collection of water and incompressible materials. This material remained resilient during cold weather and was not easily punctured by stones. After about 18 months, cracks appeared over the bubbles and adhesion failures developed. These adhesion failures progressed, rendering the sealer ineffective after 2 years.

The adduct-rubber sealer exhibited a gradual hardening during the first 5 months and began to tear away from the concrete as the cold weather started. On close examination it was discovered that only a thin skin or web extended between the top of the two slabs in the places that were not yet torn. This skin was dry and brittle and was easily punctured.

Because polyurethane liquid sealers were comparatively new, they were under observation for about 5 months. Some tearing of the sealer along the joint face was encountered as soon as the weather became cold.

Polyurethane foam impregnated with asphalt was supplied eight times as wide as the joint (8 by $^3/_8$ or 3 in.) so that it remained compressed to 25 percent of its initial width at maximum joint opening ($^3/_4$ in.). This was recommended by the manufacturer to prevent infiltration of water. For installation, the material was compressed between rollers to one-quarter its initial width and then with a hydraulic press to a width of $^3/_8$ in. It was extremely difficult to place the material before it had expanded to a width greater than the joint opening. The material performed well during the summer months, although heat and pressure from the expanding slabs squeezed the asphalt from some of the foam. The uncoated polyurethane foam then appeared to dry out and lose some of its strength or toughness. As colder weather widened the joint openings, the sealer failed to recover and remain tight against the slabs in the places where the asphalt had been forced out.

The preformed tape sealers, both neoprene and urethane, failed rapidly and 3 months after installation only two of the original 19 tapes remained. The primary cause of this rapid failure was a break in the bond between the tape and concrete. An epoxy-resin compound was used to fasten the tape edges, but low temperatures (40 F) the day the sealing was done may have contributed to the weakening of the epoxy. In addition, several of the tapes were severely chewed by snowplow blades and by the blade of a grader working along the shoulders of the highway. Some or all of this damage could have been eliminated had the tapes been recessed in the pavement to make them flush. Recessing was attempted, but it was improperly done and did not allow the tape to be set deep enough. Many of the tapes were also punctured by small stones, mostly at the corners of the slabs, indicating a high stress concentration at these points.

Preformed neoprene has given excellent service for 3 years with no apparent failures where the appropriate section was properly installed. The material remained flexible during the coldest weather, maintaining contact with the joint faces. It was capable of resisting puncture and has not exhibited any evidence of deterioration from weathering. The use of this material has disclosed that certain precautions must be exercised in designing the joint, specifying the width of sealer, and installing the material. The joints must be constructed to provide a predictable and consistent width to hold the neoprene sealer in compression throughout the year. Initially, the joint must be wide enough to allow placement of the sealer and the uncompressed width of the sealer tube must be at least $^1/_{16}$ in. greater than the as-constructed joint width plus the anticipated annual change in opening.

Figure 6 illustrates a section of preformed neoprene sealer before and after installation. The shape pictured is the presently accepted cross-section; however, other configurations may perform as well or better. In designing different cross-sections it should be remembered that the center of the top of the sealer must fold down when compressed into the joint so that it does not protrude above the pavement surface.

During the winter of 1961-62, observations of the neoprene sealer installed on two contracts the previous summer revealed that the sealer was not in compression and in some instances was loose enough to drop to the bottom of the joint. This prompted a review of the data available on annual change in joint opening which revealed that 90 percent of the joints spaced at 61 ft experienced an annual change in opening of $^5/_{16}$ in. or less. As a result, the Department presently specifies that the neoprene gasket

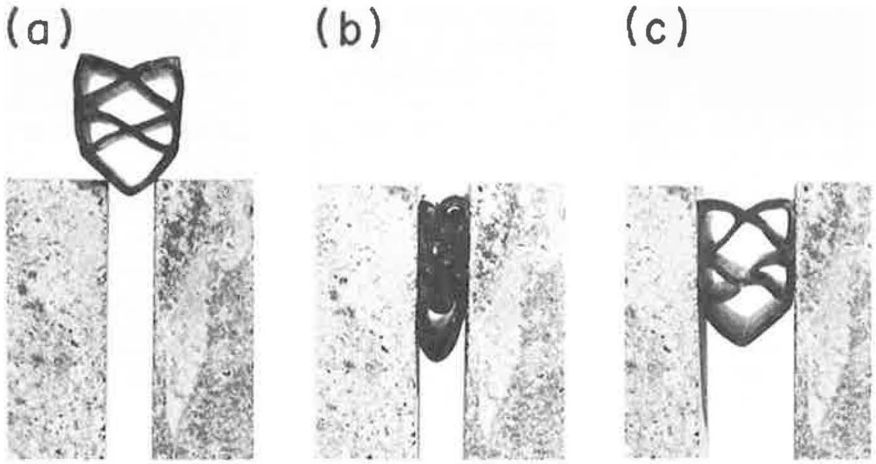

Figure 6. Preformed neoprene: (a) before installation; (b) installed in 3/8-in. joint; and (c) after joint opens to 3/4-in. in cold weather.

for transverse contraction joints must be at least 3/8 in. wider than the initial joint width.

Spalls along the joint permit this sealer to lose some, if not all, of its compression. At present, the Department requires that the spalls be repaired with epoxy resin before installing the neoprene gasket. It is also important that the sealer tube not be placed too low in the joint. If the top of the tube is more than 1/4 in. below the pavement, it is probable that stones will become wedged in the joint, thereby causing spalls when the joint closes. Therefore, the Department specifications state that the sealer shall at all times be not less than 1/16 in. or more than 1/4 in. below the level of the pavement surface. These are maximum dimensions, the intent being to have the sealer approximately 1/8 in. below the pavement surface.

Installation of the neoprene tube is preceded by an application of lubricant adhesive to the joint faces. This liquid facilitates the insertion of the sealer tube and fills slight irregularities in the joint face which might otherwise remain open. Observation of instances where the joint opening has exceeded the initial width of the sealer tube revealed that the lubricant adhesive had torn and was, therefore, not capable of stretching the neoprene. However, the adhesive is beneficial in that it does prevent the sealer from being forced to the bottom of the joint in the winter when compression in the sealer is minimal.

Since the sealer cross-section is reduced when the tube is stretched, it is very tempting for the installer to do so when placing the sealer. The sealed joint may appear satisfactory but the neoprene under continued tension may tear, or when the joint opens, the sealer tube will contract, leaving a portion of the joint unsealed.

Considering the outstanding service which this material appears capable of providing and being aware of the problems associated with its use, the Department has recently amended the specifications to permit only preformed neoprene joint sealer on new construction.

CONCLUSIONS

Installation of joint sealers in transverse contraction joints (3/8 in. wide, spaced at 61 ft) throughout the state and in two special test areas near Albany has provided the basis for appraising their performance. Observations of the test area installed in 1963 are not complete; however, there are no indications that the results will be substantially different from those of the earlier field tests. Therefore, based on field observations of joint seal materials for 5 years, the following conclusions appear warranted:

1. Preformed neoprene has given excellent service for 3 years. There have been no apparent failures where the appropriate section was properly installed.
2. Polysulfide with extenders and polysulfide tar performed well for about 18 months and 12 months, respectively, before beginning to deteriorate. Polyurethane-based liquid materials exhibit a rate of deterioration similar to polysulfide tar after 6 months of observations in the Delmar test area.
3. Hot-poured rubber asphalt gave variable performance, never maintaining an adequate seal for more than 1 year and usually failing in adhesion during the first winter.
4. Latex with extenders, rubber asphalt cold-poured with solvent, and adduct rubber have provided very poor service, failing when the weather first turned cold.
5. Polyurethane foam impregnated with asphalt sealed the joints until cold weather when the sealer failed to recover as the joint opened.
6. The neoprene and urethane tapes were punctured and pulled from the pavement by traffic or snowplows after 2 months. However, the lack of adhesion can probably be attributed to the adverse weather conditions during installation.

Factors in Joint Seal Design

EGONS TONS
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Recent theoretical and experimental investigations have helped to explain the behavior of one-phase (solid) extension-compression type joint and crack sealants and have revealed their limitations. If a one-phase, constant volume sealant has to go through a tension cycle, two situations are possible: (a) if the sealant is elastic with no permanent deformation and stress relaxation, long-term stress on the bond interface coupled with imperfections in the bond and water effects can result in adhesion failure of the seal; or (b) if the sealant undergoes permanent deformation (accompanied by stress relaxation), the stresses on the bond may become small (or negligible), but the shape of the sealant is distorted. This again may result in inability of a sealant to perform its function.

It is apparent that a seal which can retain its shape and not place any tensile stress on the contact surface between the sealant and the joint would be more effective, at least theoretically. Recent field research has indicated that at least one type of precompressed elastic sealant which is in compression all the time promises to serve longer than tension-compression sealants when relatively large joint width variations are expected. Poured-in-place tension-compression sealants are expected to perform well in joints with quite small cyclic variations in width. Cracks can also be sealed with such sealants.

•JOINTS AND cracks are usually undesirable discontinuities induced by man or nature in a highway riding surface. Because these discontinuities are generally the weakest links in a pavement (including bridges), they are often subject to more rapid deterioration. In an attempt to protect the joint (or crack) and the area surrounding it from artificial and natural damages, the joints (and cracks) are often filled with other materials which act as protectives against the ingress of liquids and solids.

In 1953 a summary on sealants and fillers was published (5). The basic concepts discussed in this publication are still valid today. Since that time several papers have been published on the subject, and with the 1964 HRB symposium on joint sealing problems, new theories and experiences have been added to the sealing field. The purpose of this paper is to discuss some of the theoretical and practical developments and to outline possible future efforts in joint and crack sealing, with main emphasis on sealants.

FACTORS AFFECTING PERFORMANCE OF A SEAL

Success in sealing joints and cracks depends on many variables, some of which are difficult to evaluate and control. The major factors influencing the performance of a

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seal are (a) characteristics of the joint (or crack) to be sealed (including properties of the pavement material); (b) properties of the sealant to be used; (c) properties and condition of the sealant-joint (or crack) interface; (d) quality of workmanship; and (e) type of service to which the sealed joint is subjected. There may be other factors operating under certain circumstances. For instance, the effectiveness of a filler strip supporting a sealant may be important in some cases.

CHARACTERISTICS OF JOINTS AND CRACKS

A joint or crack can be characterized by its geometric shape, the changes in joint dimensions, and the materials forming the joint (or crack).

Types of Joints and Cracks

Although many types of joints and cracks can be listed if differences in details are emphasized (2, 3, 10, 20, 26, 27, 30), only a few basic types will be mentioned here. Once they can be effectively sealed, the others will not present much difficulty. The basic (difficult to seal) types of openings which are found on road surfaces are contraction joints (pavement), expansion joints (pavement), expansion joints in bridges, and cracks in any surface. A simplified cross-section of the four types of openings is given in Figure 1. The first three are introduced during construction; the last one (crack) usually is not a discontinuity planned by the designer.

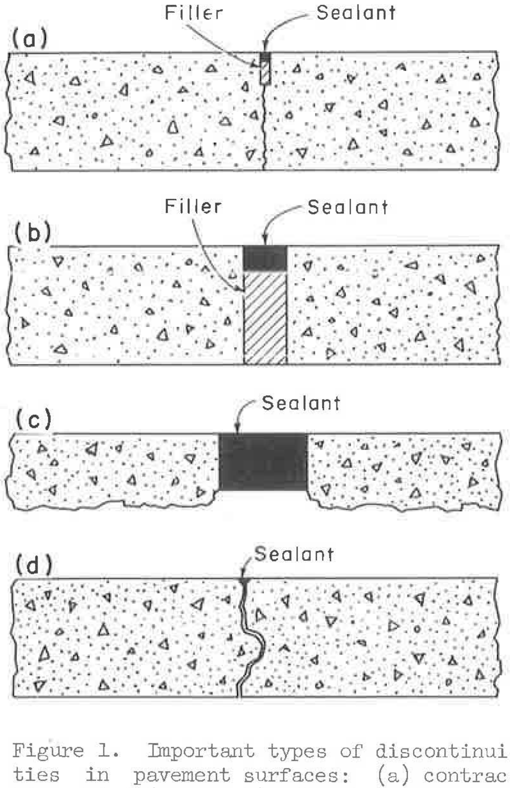

Figure 1. Important types of discontinuities in pavement surfaces: (a) contraction joint (pavement) often 0.1 to 0.5 in. wide; (b) expansion joint (pavement), often 0.5 to 1 in. wide; (c) bridge joint, often 0.5 to several inches wide; and (d) crack, often hair to $\frac{1}{2}$ in. wide.

Factors Affecting Joint (and Crack) Movements

All four types of openings are subjected to various environmental and service effects, causing horizontal and vertical movements in the slabs at the joints (or cracks). Data on vertical joint movements are lacking. Measurements taken in Massachusetts on more than 100 expansions in two locations showed the maximum relative vertical movement to be about 0.07 in., with an average around 0.01 in. The measurements were made under a 20,000-lb axle load, early in the morning when slabs were warped up.

In the case of expansion joints with 1-in. wide openings and average horizontal joint width variation of about 0.20 in. in Massachusetts, the 0.01-in. shear strain is 5 percent of the tension strain in the sealant. Therefore, the vertical deflections of pavements with expansion joints similar to Massachusetts do not seem to be very important in sealant performance. A somewhat similar reasoning can be applied to bridge joints (3). Not much is known about vertical movements of cracks and contraction joints.

Horizontal joint movement is another factor to consider when designing a joint seal. It is known that joint closing and opening depend on many factors and, therefore, the calculations are often omitted. The many field measurements available on joint movements show that in sound concrete the temperature effects are the most prominent. Thus, for instance, if the amount of joint opening per 10 F is plotted against the slab length, a straight-line relationship is indicated as shown in Figure 2. The top curve is based on unrestricted expansion and contraction of the concrete slab, using a thermal coefficient of expansion equal to 0.000006 per degree F. The middle curve was obtained by plotting the maximum joint width variations from two Michigan test roads (3) and adding data from Massachusetts and other states. The lowest curve was obtained by plotting "overall average data" for all kinds of joints in New Jersey (3). Even though local variations in different regions and projects will be present, Figure 2 may be of practical use for estimating the amount of joint opening in portland cement concrete pavements.

With cracks, the problem is slightly more complicated. If there is no reinforcement in a cracked portland cement concrete slab, the cyclic crack width variations can be approximated from Figure 2. In the case of bituminous concrete pavement, it is difficult to obtain reliable values for variations in crack width because the material is not elastic. The average thermal coefficient of expansion between 0 and 80 F is about four times higher than that of portland cement concrete (no friction case).

To summarize, the upper part of the joint which is going to receive the sealant is usually rectangular in cross-section and, in the case of road surface joints, the variations in width can be predicted. The cross-section of cracks is varied, and there are problems in introducing the sealant in the crack and predicting how much the crack will open. Effect of vertical movements on joint seals may be negligible in wide joints but needs further study.

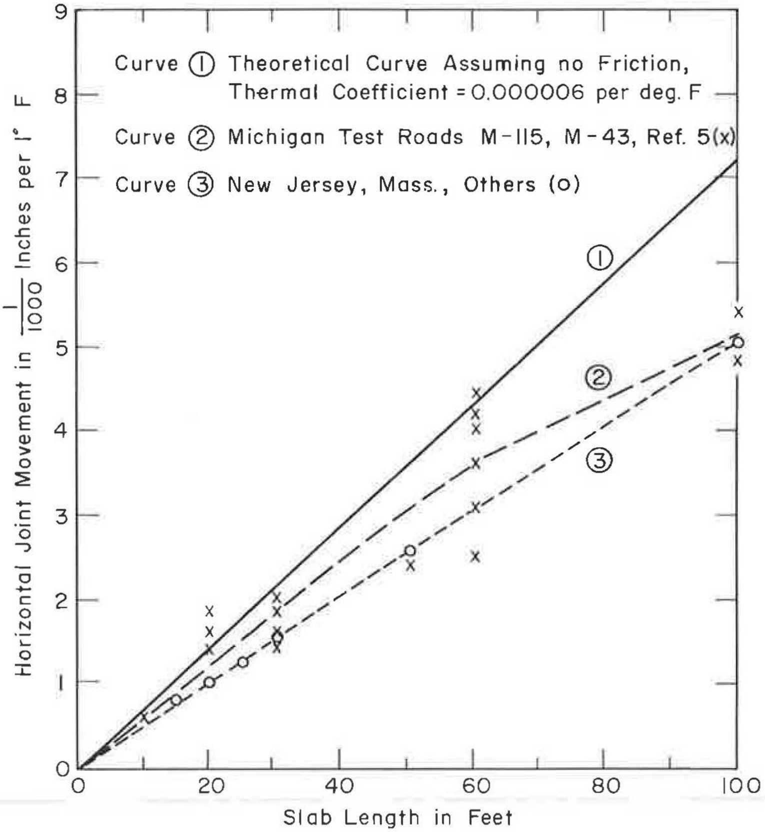

Figure 2. Joint spacing and movement.

PROPERTIES OF SEALANT TO BE USED

It is apparent from the cross-section of a joint (or crack) in a pavement that the plug of the sealant placed in the joint will be similar to a short single-span bridge fixed (glued) to two abutments which move back and forth in opposite directions with temperature changes. In addition, the two joint ends (abutments) may have considerable movement in the vertical direction due to wheel loads (joint deflections). To design a bridge for such conditions is obviously not an easy task.

The closing and widening of a joint (or crack) causes strains in the sealant. These strains can be predicted for one-phase (solid) compounds which do not change their volume while in the joint (29).

For sealants, in general, three distinct stress-strain cases can exist:

1. The sealant is sometimes in tension and at other times in compression (stress reversals);
2. The sealant is always in compression; and
3. The sealant is always in tension.

The first case is the most common in present road joints (and cracks) and, therefore, is discussed in more detail.

Stress Reversal Case

If a joint or crack is sealed with a one-phase (solid) sealant in warm weather while the joints (or cracks) are at their minimum width, the sealant will first undergo a slow tension cycle as the slabs gradually cool down (fall and winter) and then a compression

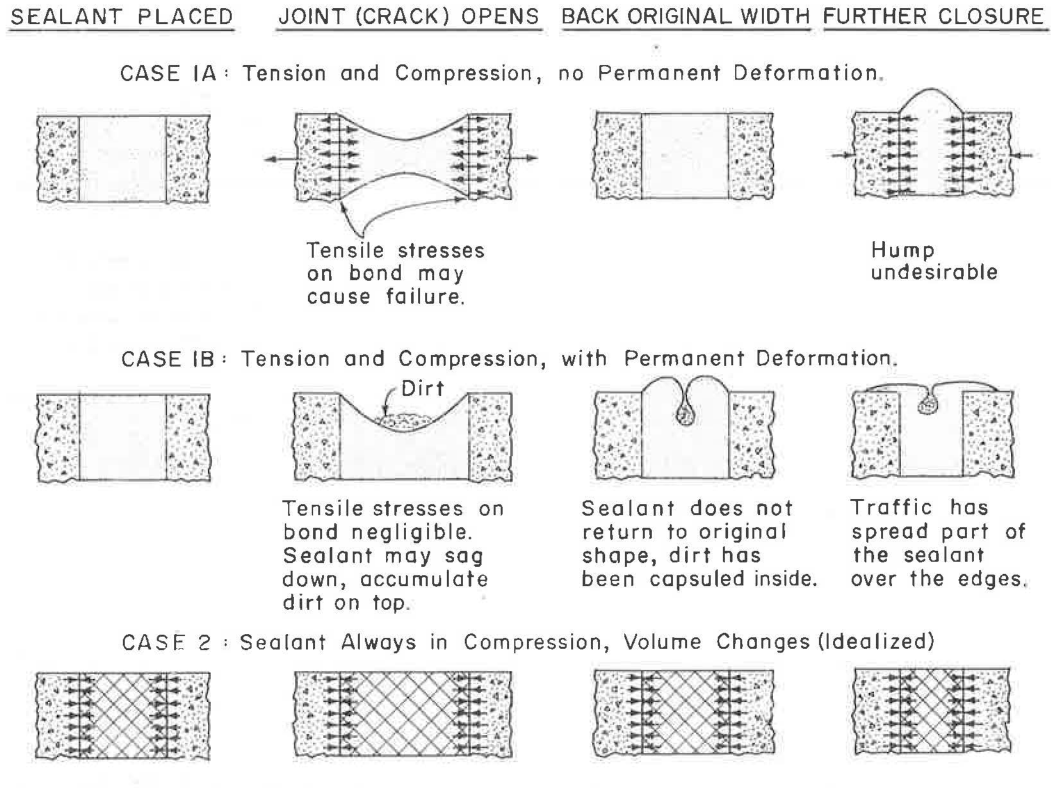

Figure 3. Conventional tension-compression sealants compared with compression-type sealants (uniform support underneath).

cycle during the second half of the service year (spring and summer). Superimposed on this long extension-compression cycle are daily variations of joint width.

In the analogy of a bridge span glued to abutments which move back and forth, it is apparent that a material spanning the joint will be strained. Depending on the type of sealant used, this strain may be recoverable or nonrecoverable (Fig. 3). Assume the abutments have moved apart and extended the sealant. This is followed by a compression cycle. If the strain of the sealant is recoverable, the sealant plug will return to its original shape and the "bridge" will continue to serve. If the stretched-out sealant is not able to recover from the tensile strain, it will lose its shape during the compression cycle and buckle (sag) down (or up) in the joint. If this sag is excessive, the "bridge" may be considered as failed (3).

In the case in which the sealant fully recovers its shape after an extension-compression cycle, the permanence of the bond between the sealant and the joint wall needs more attention because of the elastic property of stress proportionality with strain. Such a sealant at the end of the extension cycle will have a steady stress on the bond and, due to imperfections in this adhesive bond or due to service influences, the sealant can peel away from the joint interface.

From the foregoing brief discussion, it is apparent that both purely elastic sealants and those which exhibit permanent deformation under strain in service may fail when stress reversals are present (tension and compression) and the amount of joint movement is relatively large. This has been observed in the field. Many joints (and cracks) sealed in the past with the sealants alternating through compressive and tensile stress-strain cycles, have shown adhesion failures and distortion in the sealant shape (3, 7, 18, 19, 27). The changes in shape of the sealant have often been unpredictable and difficult to control even when a good filler support was present (8).

It must be emphasized that in cases where the variations in joint and crack width are relatively small and the sealant has a good support, many sealants may serve well even under stress reversals.

Compression Case

In this case, the sealant would be placed in a joint so that it is always in compression, no matter what the season. Only a material which exhibits complete strain recovery can be suggested for a compression-type sealant. A sealant exhibiting permanent deformation and stress relaxation will flow and change its shape while the joint is closing. It will be in tension as the joint opens to its maximum width (if the sealant is adhering to the joint walls).

The main advantage of a compression-type sealant is that it does not impose any significant stresses on the bond or contact interfaces between the sealant and the joint. The sealant is placed in a joint while compressed so that at all times during the closing and opening of the joint, only compressive stress is present in the material (7).

Besides having the ability to recover, a sealant should change its shape as the width of the joint varies so that there is no objectionable protuberance of the sealant above the pavement surface (hump) and no deep curve-in below the surface of the slabs (causing progressive accumulation of solid matter). This can be achieved in various ways, for example, by introducing gas (air) into the sealant plug to make it compressible so that it can follow the volume of the joint.

Tension Case

Pretensioning a sealant before placing it in a joint and holding it in tension is difficult and impractical in road joints. The situation is similar to the first (tension) part of the stress reversal case.

PROPERTIES AND CONDITION OF SEALANT-JOINT INTERFACE

A sealed joint can be compared to a combination of two concrete blocks glued together with a thick layer of adhesive (sealant). If the two blocks are pulled apart until failure takes place, this failure can occur in (a) the adhesive itself (the sealant fails in cohesion); (b) the adhesive-adherend (block) interface; or (c) the adherend (block). In the field, one of the most frequent failures in joint seals has been along the adhesive-adherend interface (bond failures) in spite of the fact that laboratory bond-ductility tests have shown no signs of weakness in adhesion. If there is a true bond between the polymer (sealant) and the concrete block, the sealant should fail in cohesion rather than in adhesion.

There are several explanations of the large number of bond failures. The most common are as follows:

1. Laboratory bond test blocks are carefully prepared. On the road, the surfaces of the adherend (concrete) are not clean but contain fine solid particles, moisture and possibly other adsorbed matter. It is difficult, if not impossible, sometimes uniformly to clean and prepare the surfaces of the adherend to receive the adhesive (sealant). Therefore, built-in bond weaknesses are present from the very beginning.
2. Portland cement concrete paste and mortar contains pores (or voids), part of which frequently contain water. The water can also migrate to the bond interface and affect it. This may be especially destructive during freezing when quite high pore pressures can exist if any part of the concrete gets saturated with water which will convert to ice. Such pressures would also be developed at the bond interface, possibly causing spotty separations between the sealant and the concrete.
3. Numerous load applications accompanied by vertical movements of the slabs and abrasive action of the tires, especially after sanding, can also contribute to at least a localized bond separation.
4. During the joint widening cycle, the sealant and the bond interface are in tension all the time unless complete stress relaxation takes place in the sealant.

From this it is apparent why so many joint seals which have undergone tensile stress cycles have failed in adhesion. This loss of bond is often a long-term phenomenon.

If a satisfactory sealant can be developed which, during the extension cycle, does not build up tensile stress at the bond interface, adhesion failures should be less frequent. Such a sealant would have to be placed in a joint which opens a relatively small amount and also gives good support to the sealant (using a filler below). This type of sealant has to be used for crack sealing in bituminous concrete. If a sealant without the ability for stress relaxation during the extension period is placed in a crack in bituminous concrete, the bituminous concrete itself may fail in tension, thus creating a new crack nearby.

Sealing cracks in portland cement concrete or bituminous concrete is a frustrating undertaking. Adhesion is a problem, and also the proper width-to-depth ratio often is almost impossible to maintain. The cracks have irregular alignment and width. In narrow areas, the sealant does not penetrate the crack; in wider areas it goes down too deep. One remedy for this is to use a grooving machine and widen the whole crack to a certain width, thus obtaining a uniform width crack with a freshly cut exposed surface to receive the sealant (27).

A special case in crack sealing is that of reflection cracks which are found in bituminous concrete surfacings over portland cement concrete slabs. The most critical areas are usually the transverse joints where the cracks close and open as the slabs expand and contract, causing relatively large variations in the crack width. Using present methods, such cracks have to be resealed every one to three years (27). Reflection cracks may be avoided by sawing grooves in the bituminous resurfacing before the cracks have appeared. The sawed openings are then filled with a sealant (30).

OTHER FACTORS OF INFLUENCE

In addition to the joint-sealant properties, there are other factors which may influence the performance of the seal:

1. Conditions During Placement. —Although sealing sounds like a simple operation, the skill and patience of those responsible for placing the sealant are very important. There is a difference between a sealed joint and a filled joint.

2. Service Conditions.—The length of service expected from a sealant will depend on the amount of traffic on the road and the environmental conditions to which the sealed joint is exposed. Also, a tight seal is more desirable for highly traveled roads (many load repetitions) to protect the support from weakening effects of water.

SUMMARY

1. Concepts of quantitative analysis have entered the joint sealing field. It is possible to predict (or design for) a tensile strain in a solid-type rectangular cross-section sealant plug under varied conditions.
2. Theoretical calculations and practical experiences, however, show that for large joint width variations, the strains (and stresses) in the solid-type seal are high and frequently result in failures. Bond failures are especially numerous.
3. Compression-type (two-phase) sealants show promise theoretically and in practice. Their prime advantage is that adhesive bond is not needed.
4. Poured-in-place solid-type sealants with stress reversals while in service may be used in joints which induce low strains in the seal. Also, all cracks are to be sealed with such sealants.

RECOMMENDATIONS

There are several problems which need attention, including:

1. Performance criteria and evaluation tests for compression type and tension-compression sealants;
2. Adhesion problems in poured one-phase sealants used in joints and cracks;
3. Field measurements of vertical joint movements;
4. Effects of shear stresses and strains on sealants in pavement joints and cracks; and
5. Possible methods and materials for sealing irregular cracks.

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A Structural Approach to Sealing Joints in Concrete

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•SEALING OF joints in concrete pavement often is termed an art. Whether this designation dignifies or belittles the process, its implications are scarcely reassuring to highway engineering which strives for performance based on definitive appraisal of cause and effect. Shortcomings in existing practice are documented too well to require recitation, except to observe that the incidence of random failure should not be unexpected since the solid-fill technique is analogous to plugging an enlarging hole with an undersized cork. Accomplishment of such a feat assuredly demands a high order of ingenuity. I submit that technical effort based on such an approach, or simply in pursuit of tradition, might better have been directed toward clearer definition of the problem and a more effective solution.

SCOPE

Although the principles developed herein may have broader application, this paper is concerned chiefly with the sealing of joints which gap substantially with contraction and expansion of the joined sections of pavement. The basic requirement is that of fully occupying at least the uppermost portion of a changing rectangular section whose width may vary in ratio of 1:2. One of the more obvious ways to occupy such a space is to fill it with a volume-variable composition such as sponge rubber. Attempts to use foam latex appear to have been unsuccessful, due to its inability to prevent gravel and other foreign matter from becoming imbedded and trapped within the joint space.

DEFINITION OF THE PROBLEM

Instead of using the slot as a mold, we may approach the subject as a structural engineering problem, that is, to provide a bridge between two concrete abutments. Unlike ordinary bridges it should be capable of doubling its shortest length and returning in repetitive cycles. In addition, it is desirable that level top surface continuity be developed across the span. Since the exposed surface is subject to abrasion and to a variety of hazards, it should be as durable as possible. And finally, having defined the structure as a bridge, let us attempt to endow it with structural capability.

STRESS

Since this is to be a designed structure, we must first determine which of the several stress-strain principles to use: compression, tension or stress reversal. The individual cases for these three approaches have been outlined definitively by Tons (1) and indicate that tensioning the seal, whether constantly or intermittently, invites trouble. There are five links in each tension chain: the centrally positioned sealant, its bond to each of the abutment surfaces, and the supporting sections of concrete. Sufficient weakness in any one of these may cause failure. It is significant that as the span widens, the sealant is more demanding of its anchorage, not only because of the distention but also because of its increasing modulus of elasticity as temperatures fall. Except for such relaxation as may be tolerated in certain stress-reversible sealants, the demanding factors in a tensioned system thus tend to compound rather than to alleviate. The

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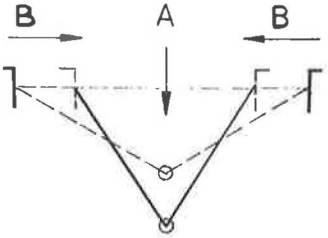

Figure 1. Hinged lever principle.

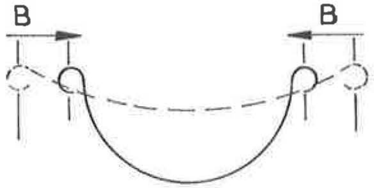

Figure 2. Spring principle.

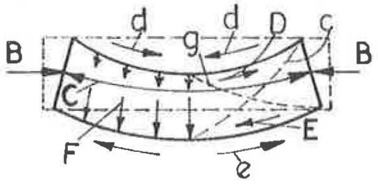

Figure 3. Elastomeric spring principle.

spiraling of such factors, the marginal security of tensionable anchorage to and/ or within the supporting concrete abutments, the skill demanded in execution and the many precautions which must be observed in both slotting and filling, as well as imponderables such as vapor pockets in the sealant and undetectable fracturing within the concrete, certainly dictate that any approach involving chain tension should be questioned and that compression must be given serious consideration. Although stress reversal is a compromise intended to relieve the two extremes, it is incompatible with stress dependence in a structured element. It will be ruled out of consideration for this reason and because it involves chain tensioning in the more dutiful portion of its cycle.

DESIGN PRINCIPLES

Since we have set out to design a structural element, defined it as a bridge, determined that it should be compression principled and made of durable material(s), or compositions which are not necessarily volume variable, the first problem becomes one of finding means whereby the excess of filling material may be displaced as the gap diminishes in width. Instead of resorting simply to horizontal or accordion-like collapsibility, we should attempt to develop complementary vertical motion in the central portion of the structure.

One mechanism which behaves in this manner is a hinged lever arrangement pivoting against the concrete abutments, coupling the oppositely inclined sine and cosine functions of a fixed-length hypotenuse. This principle is illustrated in Figure 1, in which concrete abutments support symmetrically positioned levers which are pivotable against the abutments. This causes downward motion (A) of the hinged ends of the two levers in the vertical center plane as the abutments move inward (B), thus steepening the inclination of the levers. The areas of the two symmetrical triangles illustrated are equal when the sides are inclined 30° and 60°, respectively. Thus, if the shallow triangle were filled with a suitably deformable composition, the excess of fill would have been displaced downward as the gap diminished and the top level would be unchanged.

Similar motion is developed by substituting a spring element for the hinged lever arrangement (Fig. 2). In this example, however, the area included within the narrower half circle is greater than that of the broader but shallow arc segment. This is fortunate since the sidewall pivots must be positioned below the top surface of the pavement and, therefore, greater depthing displacement is needed to allow for the reducing volume in this upper area as the joint narrows.

Figure 3 illustrates development of the spring principle in an elastomeric substance. When a rectangular rubber block is squeezed horizontally (B), the initial pressure is applied slightly above the plane of force-balance and the block deflects downward. A square-ended eraser resembling the illustration and manipulated between thumb and forefinger will demonstrate this eloquently, and much can be learned by observation of its behavior under compressive load. First, the upper or concave section tends to shorten (d) and the lower or convex section to lengthen (e); the ends of the block tilt inward as the arced deflection progresses. Thus in direct consequence of being arcedly deflected (for the moment eliminating the effect of the external force which so positioned it) the sections are oppositely deformed arc-longitudinally, the upper being in compressive stress (D) and the lower in tension (E). Since the ends of the illustrated rubber block are free to pivot about their centers, these normal stresses maximize at the vertical center plane and diminish outward, inversely opposed by shear in angular deformation. The ends of the block thus tilt inward in equilibriumed compromise between vertical and radial inclination. A graphic explanation of the same phenomenon would indicate tensiled lengthening of the upwardly inclined diagonal (c) and compressioned shortening of the opposite diagonal (g) as shown in the right half section.

Since the deformation characteristics of rubber and rubber-like elastomers are conspicuously omnidirectional, making their application to the subject purpose practical, lateral deformation also becomes significant. Because of longitudinal deformation and the normal or primary stresses above identified, quasi-radial-vertical lines of secondary stress (F) develop within the deflected section. These lines of force exhibit graded stress reversal between inner and outer termini, any given point being stressed oppositely and proportionally to the primary stress and at right angles to it except as influenced by angular deformation and shear.

The stress pattern within elastomeric structures of the types herein suggested is sufficiently complex that illustration is difficult. It will be apparent, however, that all internal stresses resulting from arced deflection compound to restore the block to its original rectangular shape, and that each contributes to opposing the external force (B); their combined force is illustrated by the arced line of compressive stress (C). This outward force is strictly horizontal and should be so indicated. It is shown as arced in the figure merely by artistic license to emphasize the similarity between the elastomeric element and the spring leaf segment of Figure 2.

Figure 4 develops the elastomeric spring concept into a designed form in which a center-notched superstructure has been added to the rectangular block of Figure 3, and the ends of its body section have been sloped outward from the vertical as indicated in the phantomed figure. Because its compressive resistance is thus imbalanced, the elastic structure deflects downward (A) as it opposes the incoming horizontal force (B) even as the extended outboard corners are first contacted. When deflected to the solid-lined position with its top surface level, the center notch is closed and its top corners are abutted. This is its maximum design width; in this position it becomes a stably stressed structure capable of fully occupying the upper portion of a joint in concrete and constituting a bridge which may provide level surface continuity between joined sections of pavement.

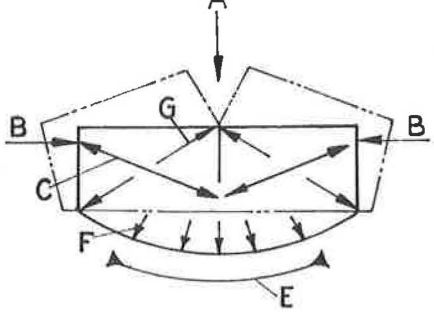

Figure 4. Elastomeric spring with center-notched superstructure.

When so compressed, lines of force (C, E, F) similar to those of Figure 3 deflectively equilibrate the structure against the support (B), and the compression (D) of the inner arc of the deflected rectangular block here is combined with the dominant compressive stress (C). Due to the addition of the top-filling superstructure and the occupancy in compression of the total upper area, cross-diagonal secondary lines of compressive force (G) begin to develop at their respective termini in opposite corners. Although such lines of stress centrally are tensioned by the dominant or primary compression (C), lateral displacement contributes by impaction to the terminal compressive force (G).

As the structure is compressed further and its central portion is lowered in increasing deformation and shear, the designated secondary force (G) increases and the line of primary force (C) moves parallelly

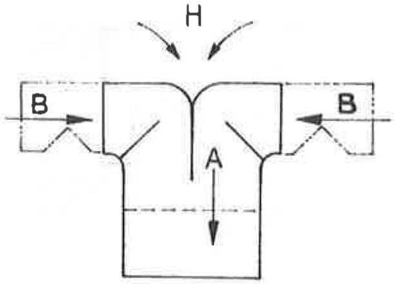

Figure 5. Rolling gland principle with strain relief.

downward; its original outboard position tends to be drawn inward as a terminus of its lengthening diagonal (c). This phenomenon is demonstrated clearly by the inwardly sloping ends of the deflected rubber block as shown in Figure 3. By oppositely sloping the ends of the modified structure, thus providing an excess diagonal, terminal compression has been maintained at the extreme corners in the maximum design width position illustrated. Although additional impaction might be tolerated, withdrawal of the top corners would tend only to be delayed rather than prevented. One remedy for such malfunction is shown Figure 5.

Figure 5 illustrates the rolling gland principle (H) which harmoniously combines the inward (B) and downward (A) movements of the top surfaces, which are transitioned between horizontal and vertical planes by recycling as the joint closes and opens. Although certain of the elements described in four previous examples may be alternative, the rolling gland principle of interplanar transition is incorporated in all of the designs herein illustrated or discussed.

In Figure 5, the elastomer is relieved of leveraged concentrations of stress which may be potentially destructive in loss of its stress memory. This principle also may be applied to the solution of specific behavioral problems such as that of top corner withdrawal occasioned by the lengthening diagonal. By notching the lower section of the structure adjacent to its supporting corners, compression relief is provided the inwardly bending moment, thus relieving the pivot-supported distention which previously had caused intolerable lengthening of the (then arced) diagonal. Although oversimplified in Figure 5, the notch simply closes as the gland rolls together, permitting the end faces to remain upright instead of tilting inward. This arc segmental relief, mentally superimposed on Figure 4, interferes little with the indicated lines of force (C, E, F, G) and thus affects only minimally the insert's load-bearing capability. Center notching the superstructure in Figure 4 also provides arc segmental relief and facilitates transition into the rolling gland, which, in effect, is initiated when the structure is first deflected.

CLASSIFICATION

The development of sealing inserts based on the principles thus far described falls readily into three groups, each separably identifiable by Figures 1, 2 and 3. These are the levered insert, the spring-supported and the elastomeric block.

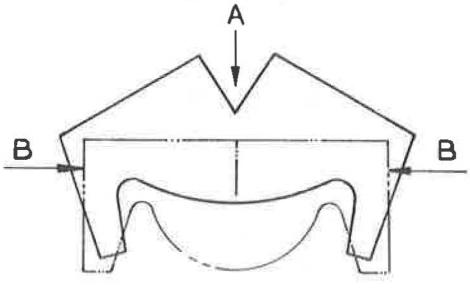

Figure 6. Prototype of solid elastomeric insert.

SOLID PROTOTYPE (GROUP III)

Figure 6 shows the form of a sealing insert based on the elastomeric spring principle of Figure 3 and developed in accordance with Figures 4 and 5. This may be considered the prototype of the elastomeric block insert (Group III). The main figure indicates its shape as originally formed, and the phantomed figure its profile when compressively (B) positioned at its maximum design width. Figure 7 illustrates its positioning in a concrete joint gapped medianly within the insert's design range. The insert is ledge supported and its top surface is flush with the adjoining concrete.

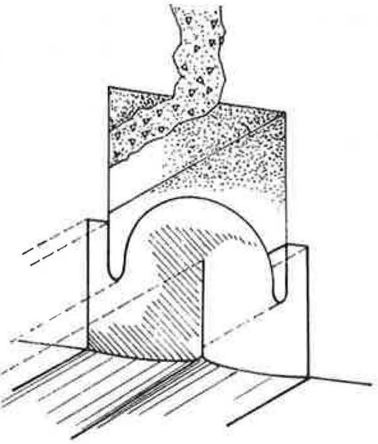

Figure 7. Solid insert installed in medianly gapped joint.

errata -Fig. 7 is upside down

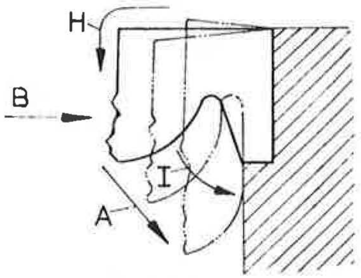

Figure 8. Progressive positioning of half section of solid insert.

Figure 8 shows a half section of the same insert of the same maximum width as is phantomed in Figure 6, and indicates its changing form as it is compressed progressively to its median and then to its minimum design width. The directional arrows (A, B, H, I) indicate motion relative to its slab-contacting edge.

Installation of this type of insert requires the use of compressive force which may be applied by a pattern of rollers, the leading pair compressing its width followed by downward force which seats the insert. Although ledge support is ideal with respect to structure and certainty of installed depth, the complications of developing such ledges in concrete could preclude their use. Alternatively, it will be recognized that such an insert possesses considerable compressive capability and that supplemental means may be used if needed to assure anchorage.

TUBULAR JOINT

Figure 9 shows a similarly patterned insert formed in a broad, relatively shallow tubular section, which becomes inversely proportioned when maximally compressed as shown in Figure 10. Here it is installed in a saw-slotted groove, beneath which the contractionally broken sections of the concrete keyingly abut each other. By connecting the lower outboard corners of the sealing insert, thereby making it tubular in section, compressible installation is greatly simplified over that of the original form shown in Figure 6, in which the tubular insert is positionable by rolling or depressing it directly into place.

LUBRICATION AND ANCHORAGE

Lubrication facilitates this method of insertion and minimizes abrasion of wall-contacting surfaces, both concrete and

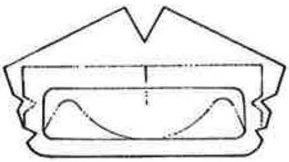

Figure 9. Tubular prototype.

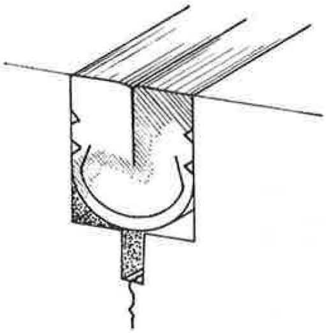

Figure 10. Tubular insert positioned in closed joint.

insert. Lubrication may comprise either a fugitive substance or a bonding element pocketed in grooves formed in the sidewalls of the insert, thus keying the interface by providing bead-formed support ledges. Mechanical keying may also be developed in this type of installation by temporarily and shallowly incorporating an evaporable solvent or a fugitive plasticizer into the outer surface of the elastomer, thus permitting stress-relaxed imaging of the opposing concrete surface and ultimate restoration of its original physical properties. Combinational means including both bonding and keying may be employed advantageously; either method may involve partial attack on the polymeric composition whether it be deformable or rigid.

RETAINERS

The assembly shown in Figure 11 also is designed for simple depressible installation achieved by containment of the sealing insert within a metal or rigid plastic clip shaped to be insertable into the prepared slot and weakened along its centerline, permitting separation when sufficiently stressed. Initial deflection of the sealing insert under downward force (A) narrows the top of the assembly and reduces its included angle, thus dropping it a little deeper into the slot and improving its wedging advantage. Continuing downward force (A′), now borne by the top edges of the retaining clip, wedges the assembly deeper, fulcrums the sides against the concrete abutments, fractures the clip along its weakened centerline and parallels its two segments, permitting the compressed assembly to be pushed without obstruction into final position flush with the top surface of the pavement.

Whereas a resilient surface under compression has measurable capacity to seal the interface against water intrusion, interposition of a rigid element demands sealing, which may be done concomitant with adhesional anchorage. Figure 11 shows external recesses (which coincidentally form internal support ledges for the elastomeric insert) in which a hardenable or semihardenable sealing composition may be pocketed to form keying beads against the concrete, as in the like-purposed treatment suggested in Figures 9 and 10.

Figure 12 shows a modified form of retainer for the same type of sealing insert, positioned in a joint which is almost closed. The retainer comprises opposed F-shaped extrusions, depthed so as to bottom supportably in the slot, with the top sections inwardly overhanging the insert. Thus, the retainer rigidly cantilevers a portion of the gap and thereby reduces the variable complementary portion spanned by the elastomer. The insert's tolerance for this type of inclosure is perhaps best explained by re-

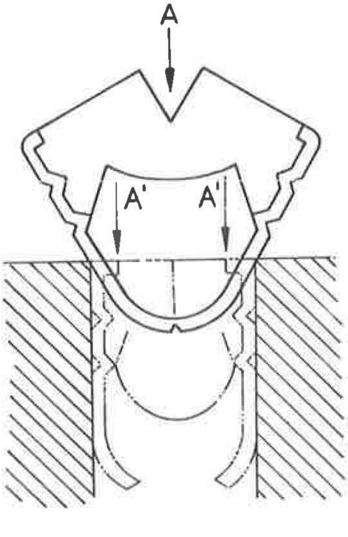

Figure 11. Clip retainer assembly.

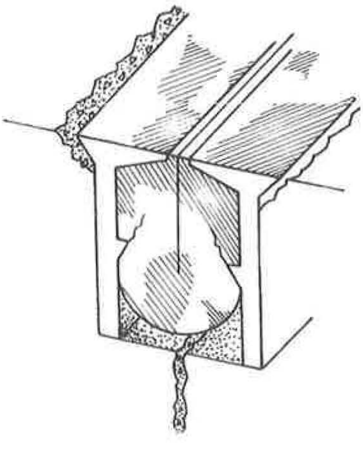

Figure 12. Cantilevered retainer assembly installed in spalled joint.

ference to the rolling gland principle (H) as illustrated in Figure 5, from which it will be evident that the outboard portions of the top surface demand no change as the gland rolls inward. It further will be apparent that deformable occupancy of the upper outboard area is nonessential to the mechanical behavior of the insert, and it will be recalled that withdrawal from this area indeed presented a serious problem until it was relieved by pivotal arc segmental relief.

Another advantage gained by cantilevering concerns control of level top surface in the closed joint. Characteristic behavior is indicated in Figure 8, wherein the top surface of the insert tends to depress at its median width and to rise when minimally gapped. Although final compression contributes to bulging by maximizing perpendicular displacement, in addition to which volume considerations are inescapable, the described phenomenon is explainable in linear terms. When interpreting behavior as a system of levers it will be apparent that these relative motions are imperfectly complementary since they mirror the sin:cos factor, which crosses unity at 45°. A comparable relationship also occurs between the depth of an arced segment and its half chord. Although the tendency of the insert to overfill a closed joint seemingly is incontrovertible, it may be controlled or prevented by use of a cantilevered retainer.

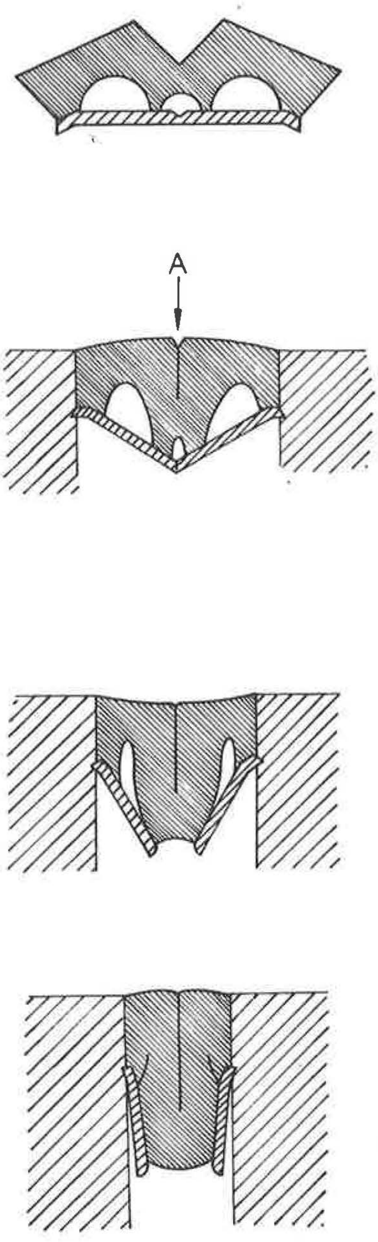

Figure 13. Levered insert with collapsible voids.

A further justification for the use of retainers concerns the problem of coping with imperfections in slot formation. One example is that of raveling in the sawing of the joint. Although width imperfections may not necessarily be grievous when flowable sealants are employed, they could seriously affect the performance of a precision insert of which maximal demand is made and in which the design specification did not permit allowance for such variation. In the case of more serious defects such as chipping or spalling, installation of a structured element likely would require some sort of retainer. Such a case is suggested by Figure 12, where the void could be filled with sealant or other suitable material.

LEVERED INSERT (GROUP I)

Figure 13 shows the fabricated form of a levered insert, based on the principles suggested by Figure 1, and its shaping when compressed in the narrowing joint. The insert comprises an elastomeric superstructure bonded to a rigid base which instead of being hinged is weakened at its centerline so as to bend along the line and to fracture when further stressed. Separation of the levers permits bottom spread and provides additional space into

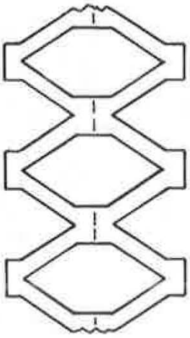

Figure 14. Expanded strip for levered insert.

which the central portion of the elastomer may depress. It also develops a compound levering motion which leans toward improvement in linear behavior at the vertical centerplane and thus favorably affects deflection of the top surface.

The elastomeric superstructure contains voids capable of occupancy by the elastomer, permitting collapsibility into a volume of space less than that originally occupied and giving the insert a wider range of operational width than otherwise would be practicable without resort to a volume-variable composition. The use of such voids extends the second principle of Figure 5 concerning relief of severe concentrations of stress and development of mechanical behavior patterns, permitting the use of somewhat tougher and higher-modulused elastomers.

The levered insert is installed simply by application of downward force to the proper depth where the sharp corners of the levers, whether cut square or shaped in the manner indicated, pivot in the supporting concrete sidewalls. Overcentering makes vertical withdrawal or suction removal of this insert mechanically impossible except by use of a tool designed for the purpose. The lever-like baseplates may be either rigid plastic or metal; the latter has greater capacity to develop pivotal grooves in the supporting concrete. This is not of particular significance except that when the joint is maximally spread and the insert minimally stressed, traffic-applied downward force might reseat the insert at a lower level.

There are also problems of bonding combinational elements, some of them simple and others complex. In the event that a particular combination is difficult or costly, it is a relatively simple matter to provide mechanical interlocking, e.g., by perforating the baseplate longitudinally and extruding the elastomer keyably in place.

There is also the problem (at least theoretical) of differential coefficients of expansion, especially when considering materials with significant linear distensibility. Lateral corrugation or spaced ribbing can prevent accumulation of such forces. The troublesome element can be segmented or, if it must be continuous, slotted relief may be provided alternately from opposite edges. Such solutions are applicable not only to the baseplates of the levered insert but also to the retaining clip shown in Figure 11. By contributing to flexibility, such expansion relief in this latter instance could facilitate its rollable installation.

Another approach, specially adaptable to the levered insert, is the use of a longitudinally expanded strip as illustrated in Figure 14, with which may be incorporated mechanical keying by extrusion envelopment, thus permitting concomitant solution of several problems and introducing additional design variables. This solution could be particularly fortunate, expecially when considering the problem of oxidation or corrosion of metal elements used in the proposed manner, since the saving in material could make economic the use of stainless steel or other corrosion-resistant alloy, requiring no surface treatment which would tend to be ineffective at the pivoting corner where the material is subject to abrasion.

SPRING INSERT (GROUP II)

Figure 15a follows the form suggested by Figure 2 and Figure 15b shows the same insert fully compressed in a closed joint. The spring insert comprises an elastomeric superstructure bonded to a spring base and collapsible voids which serve similar purposes as in the levered insert. Some of the changes in configuration are illustrative of design latitude, but the full-depthed center notch, although not essential, suggests

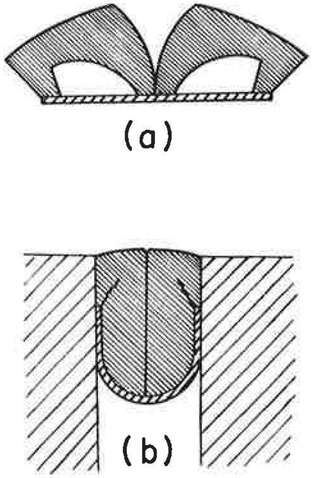

Figure 15. Spring insert: (a) uncompressed, and (b) fully compressed.

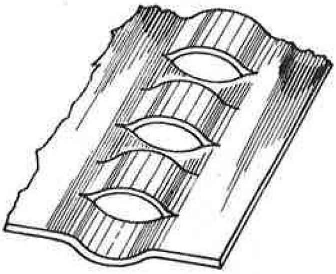

Figure 16. Preparation of metal spring element for extrusional keying of elastomer.

a basic difference; here the support element provides the spring force which in the levered insert is carried by the lower central portion of the elastomer. In other respects the two are quite similar, including manner of installation, wedge-like resistance to withdrawal and definitive pivoting against the sidewalls of the concrete.

Extrusional keying of the elastomer presents a slightly different problem since it is unwise to weaken localized portions of a spring element, e.g., by a line of perforations. However, it is permissible to stiffen relatively narrow sections without serious effect on spring action. This may be accomplished by cross-shearing and drawing the connecting segments inward and outward alternately in the manner illustrated in Figure 16.

SURFACE DEFLECTION

Despite differences in styling and construction of the various inserts, deflection of their top surfaces tends to follow the same basic pattern, depressing in the median range and rising again as the joint closes further (as indicated in Figs. 8 and 13). Although this deviation may be so slight as to make its investigation seem academic, an examination into what makes it occur is helpful both in better understanding its mechanical behavior and in developing more advanced forms.

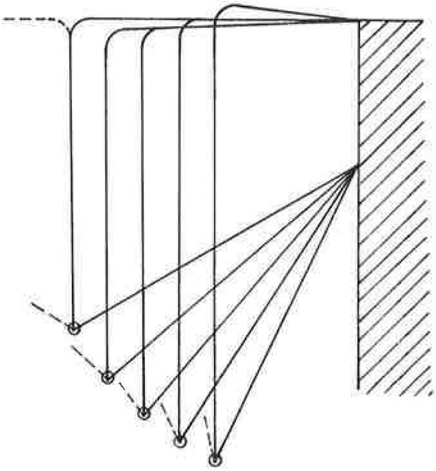

Figure 17. Deflection of hinged lever.

A linear appraisal is adequate for our immediate purpose. We may consider the top horizontal and vertical center planes and the supporting lever or spring elements as simple nondistensible elements. This technique is applied to the hinged lever arrangement (Fig. 1) in Figure 17, showing a half section with its external contour multipli-positioned relative to its outboard edge and supporting pivot. The illustration is constructed by maintaining constant the combined length of the exposed top surface and the vertical center plane, and positioning the range midpoint of the inclined lever slightly below 45°, the point of equality between sine and cosine at which vertical and horizontal motion are equal. The top surface falls and rises in the prescribed manner as the half-width diminishes.

Figure 18 shows the effect of a compound or knee-jointed lever substituted for the

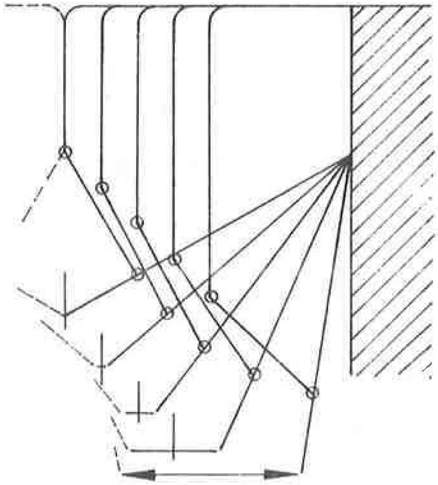

Figure 18. Deflection of knee-jointed lever.

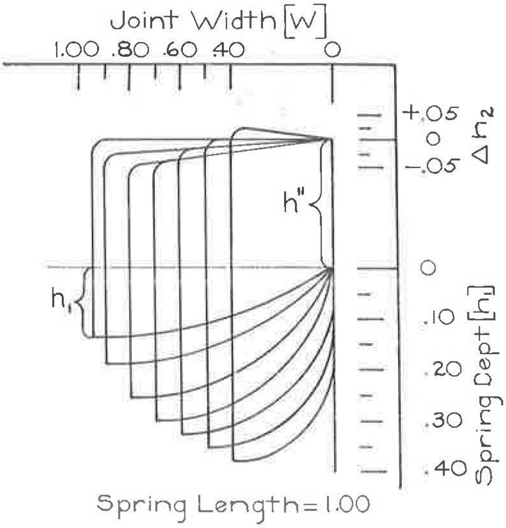

Figure 19. Deflection of spring insert.

direct-hinged arrangement of Figures 1 and 17. This illustrates the type of motion developed by the construction shown in Figure 13, wherein the levers are hinged elastomerically and flexibly somewhat in the manner of the diagram. If its actual performance were to match the stepped showing of the illustration, the top surface would not deviate from its established plane. This characteristic develops as an interesting and perhaps valuable byproduct of permitting the levers to spread to increase occupiable space for the elastomer.

Figure 19 shows the action of a spring-supported insert. This has been calculated precisely and provides specific data on its behavior. Like the last two diagrams, it shows progressive positioning of a half-section contour, but its units of width are in terms of spring length which remains constant as the chord of the arc segment diminishes with the narrowing of the joint. The indicated width range is from 0.95 (maximum span) to 0.40 (minimum), slightly broader than the specified 2:1 ratio. Vertical positioning is given in the same unit. Within the range specified, the height of the arc segment (h_1, centerline depth below the chord connecting the pivotal ends of the spring) increases from 0.134 at maximum width to 0.386 when deeply deflected. When the joint is positioned at 0.637, the full arc segment reaches 180° and thus its height equals its half chord. Beyond this point the depth combines the diminishing radius of the reducing half circle and the lengthening sidewall tangent, together providing the total depth figure given.

Initial deflection of the top surface (h_2) from its starting level position is rapid, bottoming when spanned 0.80 (spring length), then rising very gradually but at an increasing rate to 0.637. Beyond this point, the rate is constant, returning to level at 0.504, and thereafter deflecting upward above its original position. The indicated maximums of h_2 are -0.045 and +0.024. In the case of a $\frac{1}{2}$- to $\frac{1}{4}$-in. joint, there would be a depression of $\frac{1}{45}$ in. when the joint was a little less than $\frac{7}{16}$ in. wide and a rise of $\frac{1}{90}$ in. if it were over-squeezed to $\frac{7}{32}$ in.

VOLUME CONSIDERATIONS

When a solid block is deformed from a horizontal shape (e.g., a rectangle or a triangle) to an inversely dimensioned vertical form, its cross-sectional area is unchanged. Each half section of the elastomeric prototype essentially is such a block of material. Thus, its mean depth or thickness when maximally spread is limited to half the minimum width of the joint; it will be confined into this space when fully com-

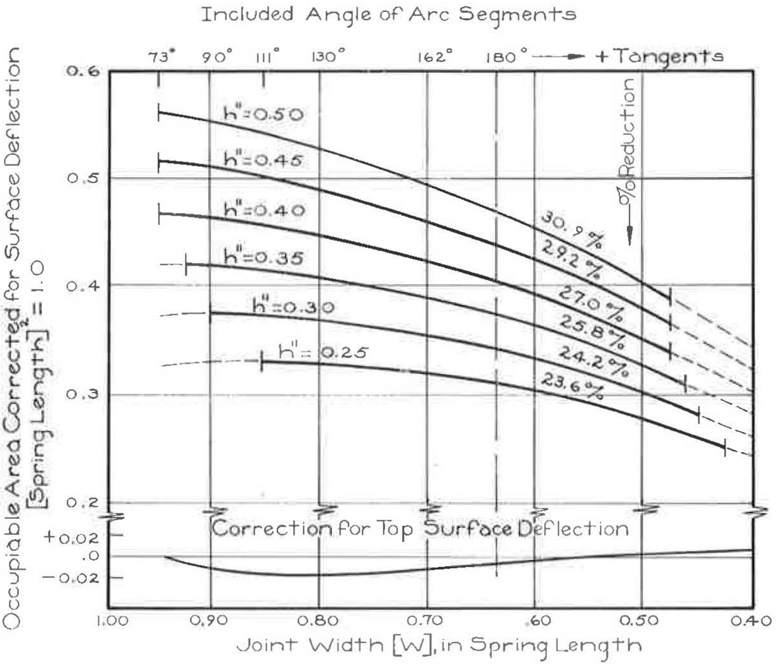

Figure 20. Cross-section areas of spring inserts with different pivoting depths.

pressed. Assuming that the insert's design width range is 2:1 and that its mean depth doubles under compression, its starting mean thickness must not exceed a fourth of its maximum span. By providing internal voids, such as was done in both the levered and the spring inserts, this limitation on initial gross mean depth may be relieved considerably. As far as gross or occupied volume is concerned, this is equivalent to using a variable volume composition, except that the voids are unified into definitive shapes instead of being dispersed. Figure 13 illustrates the progressive collapse of such voids, which permits reduction in gross volume as the joint narrows.

Figure 20 shows cross-sectional area data based on the half-section showing of the spring-supported insert in Figure 19. The units (flat spring length) are identical except that the ordinates are squared. The lower curve indicates the area lost or gained by deflection of the top surface. This set of calculations is based on linear data, whose validity in establishing the actual contour and positioning of the top surface lessens as the modulus of elasticity of the elastomer decreases. Its validity is improved, as is all linear behavior, under the opposite condition. Since one of my objectives is the use of tougher compositions, there need be less concern at this point with its application to softer materials.

The principal curves in the graph indicate the cross-sectional areas within the various contours, developed in the manner illustrated in Figure 19. The several curves differ with respect to initial depth or thickness of the superstructure (h″), or the depth below the pavement surface at which each end of the supporting spring segment pivots against the concrete sidewall. These cover pivoting depths of 0.25 to 0.5 spring length. The greater the pivoting depth, the greater is the excess volume of material for which occupiable space must be available as the joint narrows.

The optimum 2:1 range in design width is indicated for each curve; the shallow superstructures require greater initial deflection to avoid an increase in occupiable area which occurs in all cases when deflection begins.

The reduction in area, or that portion which must be voided, is indicated for each of the curves. Doubling the depth of the superstructure in the range indicated increases the void requirement by less than a third, or from 23.6 to 30.9 percent. Since voiding

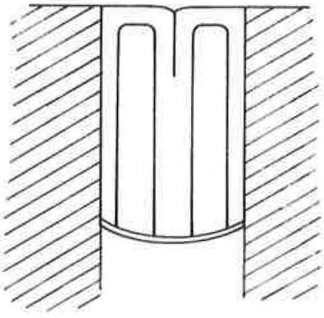

Figure 21. Deep contoured insert.

only about 30 percent of such a cross-section is a relatively modest requirement, it is apparent that greater depthing can be tolerated.

DIVISION OF FUNCTIONS

As often occurs in the evolution of a design, the obvious is not immediately apparent. Enlightenment in this case stems from the last stated observation concerning tolerance for additional depthing of the superstructure. Its basis lies in functional division of the upper rolling gland section and the lower spring support element (this division actually was made in both the levered and the spring inserts) and in the formation of collapsible voids which sculpture the opposing vertical half sections of the elastomer easily into inverted U shapes. Once narrowed sufficiently to permit containment within the closed joint, the vertical connecting legs may be extended indefinitely without change in their newly conceived function, allowing the spring support or motor element to be positioned at any desired depth in the joint. Thus, the deep contoured insert evolves as illustrated in Figure 21, which is classified as Group IV.

MOTOR ELEMENT

Of these separated elements, the motor segment should be first investigated more critically. Although the basic pattern of deflective behavior tends to complement the closure of the joint, the pattern is not without fault. The data previously presented were ideal calculations based on the use of a metal spring element having no thickness. Because in most applications the motor element is likely to be elastomeric and thick, the data must be corrected for the lessened span between pivots. In addition, the rate of descent must be variable to allow for differences in demands of the surface section and in the linear behavior of elastomers of various moduli. Although the deflective behavior of arced sections is incontrovertible, we are not without means for its modification.

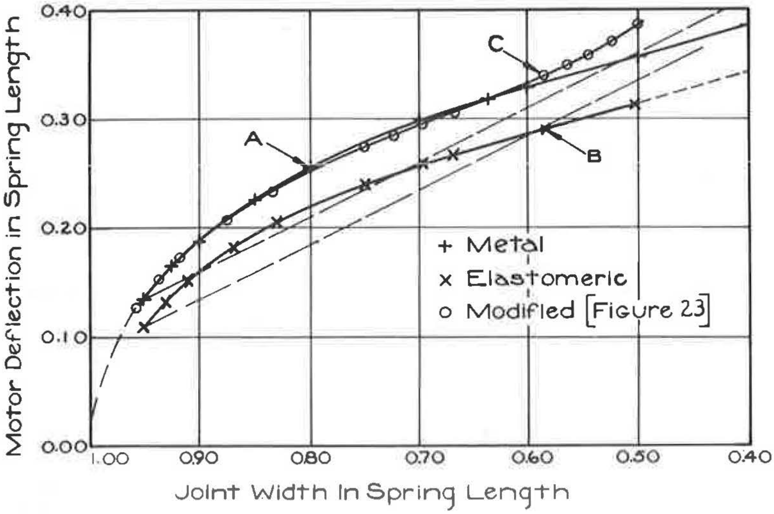

Figure 22. Comparative vertical motion of three motor elements.

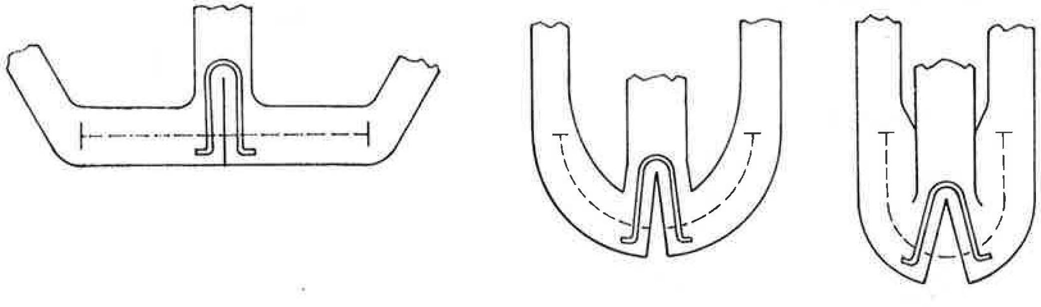

Figure 23. Modified motor element (Curve C in Fig. 22).

The curves in Figure 22 compare the deflection of three motor elements as the joint varies in width. The diagonals indicate perfect depthing relative to the starting points of each of the curves, the two upper curves bearing to a common diagonal. Curves A and B cross their respective diagonals and thus their top surfaces protrude above the pavement when the joint is closed. Curve C does not cross, but tends rather to parallel under the same condition.

Curve A is based on the ideal calculations of a metal spring element having no thickness. Thus, its pivots span the exact width of the joint. Curve B shows the motor action of a simple elastomeric element of uniform thickness (0.22 of net spring length) pivoted inward from each supporting abutment a distance equal to half its thickness. This also is an ideal curve since it presumes perfect mean circular arcs and radii, unchanging spring lengths, and constancy of pivotal positions. In addition, it fails to allow for lateral vertical displacement of the inner arced segment occasioned by increasing compression as the radius shortens. Thus, the effective depth of deflection would be less than the curve indicates and this deviation would increase as the joint narrows.

Curve C charts the behavior of a modified elastomeric element of uniform thickness (0.20) pivoted as that shown in Curve B. This also is a theoretical curve because it is based on the same assumptions. Two added factors account for its difference: (a) the spring length increases as a function of flexure (calculated in terms of opposed stresses, each levered proportionately to mean radius), and (b) it includes an equivalent of the compound levering action previously suggested in the discussion of Group I (levered) inserts and illustrated in the knee-jointed arrangement of Figure 18. In addition, it eliminates the principal source of the last-named error of Curve B by anchoring the central vertical leg to the body of the arced section rather than to its inner top surface.

Both of these contributive factors have been accomplished by the modification illustrated in Figure 23. An inverted U-shaped metal spring segment has been molded into the motor element at its center. The elastomer shrouds the metal but is disconnected at the center plane, thus permitting the metal spring segment to open to the degree that it is stressed without tensiled interference by the connecting elastomer. Being well anchored, especially along its lower edges, the metal insert becomes an integral portion of the deflected arc segment, which behaves in a normal manner except that its mean circumference (spring length) increases as the metal insert opens under greater stress and leverage as the radius of the deflected arc shortens. The second factor derives from the lowering of the pivot of the metal spring insert as it opens under stress. Both the spring lengthening and the levering factors accelerate their contributions to vertical motion as the deflective radius shortens, together accounting for the favorable behavior of Curve C in its lesser spanned range, thus bringing the closed joint portion of the curve under control.

We now attack the initial end of the curve, where the deflection is too severe. Curves A and B show an inadequate but constant rate of deflection when their net half widths equal their heights, this being the point at which the full 180° arc is developed and the deflected element becomes a rolling gland with an ever-shortening radius and its excess

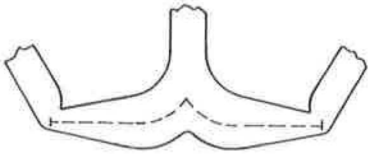

Figure 24. Constant rate motor element.

circumference laid out in tangents against the supporting abutments. The root factor of vertical to horizontal motion here is 0.57 $\left(\text{or } \frac{\pi}{2} - 1\right)$ and, thus, the vertical motion is inadequate. Even though we have learned how to compensate for this inadequacy in the closed portion of the range, it would seem inadvisable to attempt the amount of compensation necessary if the full 180° circular arc were initiated at the maximum span. Instead let us make partial use of this full-arced phenomenon by tapering the thickness of the motor element, deepening its center and shallowing its ends. Initial deflection of such an element becomes shallow elliptical rather than circular or vertically elliptic. Thus the depth of the arc segment is lessened and the more flexible outboard ends are merged tangentially with the supporting abutments in the manner of the full circular arc, thereby introducing a controllable amount of full arced behavior early in the deflective cycle. By combining this treatment of the initial curve with the spring-lengthening technique, it is indeed possible to develop vertical motion approaching perfection.

Figure 24 combines these principles in an elastomeric motor element. By reversing the central portion of the arc so that under strain it resembles an inverted V, the design incorporates the lengthening and levering phenomena of the spring-modified element shown in Figure 23.

DESIGN OF TOP STRUCTURE

Development of the deep contoured insert (Group IV) also permits specialization of the top structure, which becomes an ideal application of the rolling gland (Fig. 5). Although the motor element is highly demanding, especially when great range is required, the surface structure is freed from the manifold problems of drastic deformation, and its elastic requirement is that of simple but relatively sharp flexure. Figure 25 illustrates the type of action to which it is subject; the sketch shows progressive positioning of one of the opposed half sections.

It will be noted that the rolling section is tapered. Since horizontal compression increases as the joint narrows, tapering helps to maintain relative constancy of the external radii of the intermating arcs. These, of course, will flatten abruptly as they merge at the vertical centerplane in the same manner as the surface of an automobile tire is sharply radiused and its surface stretched as it meets the pavement. This tapering also reduces the amount of upward force (K) required to square the rolling section when the joint is open and thus lessens the work required of the motor element

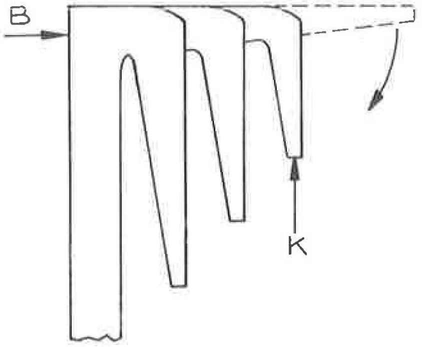

Figure 25. Progressive positioning of tapered rolling section.

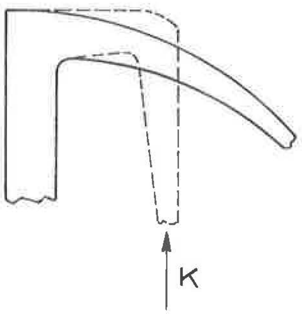

Figure 26. Curvilinear section, strain relieved in flexure by reverse prestressing.

when it is only partially deflected. This can be significant since the motor element's positive force is downward rather than supporting.

Figure 26 shows the rolling section formed as a tapered arc, which best adapts itself to the design of the total insert. As the gland is squared into closed position, the flattened sections are oppositely prestressed, thus relieving to some degree the strains which occur in sharp flexure. Although this design may require a slight increase in vertical motor force (K), the leverage against horizontal compression approaches infinity. By tapering the rolling section, the mean horizontal force inclines slightly upward, forming an inside angle of less than 90° from vertical when the top surface is leveled, thus overcentering the opposed horizontal forces. When so positioned, the compressive resistance of the horizontal sections partially relieves the motor element of the indicated need for vertical support, conceivably with the possibility (however improbable) of stress reversal of such support. This further indicates the importance of the role played by the motor element wherein perfection in its design can reduce its work load, permit reduction in thickness and severity of deformation, and thereby improve its performance and service life.

BUTTERFLY INSERTS (GROUP IV)

Now let us put these elements together in a deep contoured insert nominally depthing twice the maximum joint width. Figure 27 shows a series of such inserts in which the center leg is split to varying depths, each performing identically when squared in the joint. The outboard sections are arced and thus can be stressed into pressured contact with the supporting concrete.

Most tubular inserts may be installed by forcible depression into place, but they will differ in how reliably they may be depthed. Although lubricity at the pressured interfaces affects placement, force applied directly to the mechanics of deformation is more positive. For example, in the tubular insert shown in Figures 9 and 10, downward force applied to the top center of the superstructure brings the bottom surface of the motor element immediately into contact with the lower membrane and draws the sidewalls of the insert into place. However, if the sidewalls were pressed downward, relatively minor changes in frictional resistance would result in different placement. Similarly downward force applied at the base of the center notch of the butterfly insert will deflect the motor element and draw the sidewalls into the joint space behind it. The most certain application of such force would occur in the insert having the deepest notch, thereby minimizing reliance on elastomeric transmission to the motor element. Thus, insofar as reliability of installation is concerned, the lesser modulused elastomers would require the deeper separation of the center support.

Alternatively, it may be necessary to improve the dimensional stability of the center support so that deflection of the motor element is reproduced more faithfully at the top surface. Figure 28 introduces such a stiffening element molded within the center support section. It will be apparent that the stiffening element could comprise the total center support, especially if surface protection were not needed, and that the complete insert might be coextruded of dissimilar compositions.

Since the stress-strain requirements of the various elements differ so markedly from each other, further compositional specialization could be dictated, especially for critical applications demanding maximal performance. Furthermore, in all cases

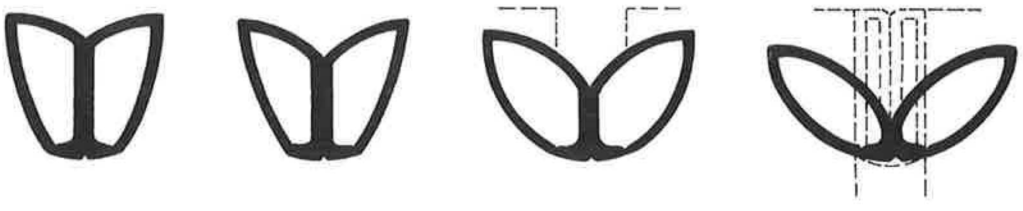

Figure 27. Deep contoured butterfly inserts.

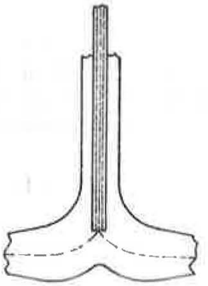

Figure 28. Stiffened center support section.

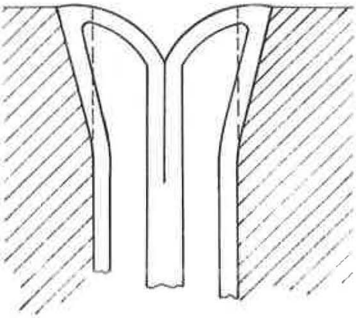

Figure 29. Sealing flared slot.

the surface sections are exposed to hazards such as abrasion and exposure to sunlight from which the motor element may be shielded. This is mainly shown by jet aircraft ramps and runways, especially in engine starting and warm-up areas where the seals are subjected to localized heat, fuel and flame.

Although Group IV inserts may be formed effectively in low-modulused elastomers, the design is adaptable to much higher polymers than were heretofore deemed feasible for variable gapped sealing. Thus, it is not inconceivable that hitherto impossible specifications may be met satisfactorily. Due to the increased stiffness and durability of such materials and their potentially reliable use in lesser cross-section, combined with suitably compositioned motor elements designed for longer stroke, the range of operable width may be extendible beyond the 2:1 ratio originally specified. In addition, as progressively harder compositions are used in the outer vertical and top surface sections, the butterfly insert more closely resembles externally the cantilevered retainer assembly illustrated in Figure 12.

The inserts earlier presented in this paper and classified within Groups I to III require horizontal containment within reasonably close limits relative to the designed width. Indeed, one of the purposes of the retaining elements (Figs. 11 and 12) was to permit their effective use in malformed slots. In contrast, the deep contoured butterfly inserts have considerable tolerance for slot irregularities above the level of the motor pivots. Figure 29 shows the insert positioned in a fully opened joint with its exposed surface 100 percent wider than the specified minimum. The rolling sections still join compressively but at a lower level; in this particular case the centerline surface is depressed about three-quarters the amount of the overwidth.

REJECTION OF FOREIGN MATTER

When installed in reasonably width-toleranced joints—this applies to all inserts discussed—the radii of the intermating arcs is so exceedingly short adjacent to the actual point of center plane contact, due to the opposing sections being forcibly impacted together, that none but the tiniest of particles could be carried inward as the joint closes. Such inconsequential matter as may be seized will be rolled out and freed in the reopening phase of each cycle. But in the extreme example shown in Figure 29, the converging sections are less impacted and thus larger radiused in this critical area. When subjected to greater proportional slot overwidths, the centerline mating is more deeply depressed and longer arc segments become wedge-inclined and capable of seizing ever-larger particles. When this occurs, a most interesting phenomenon develops: the seizing of such a particle separates the opposing surfaces and thus shortens the distance which the top sections must span. Each inclusion tends to correct the operative width of the insert. It is not improbable that the center fill of foreign matter may indeed tend to duplicate the overwidth contour of the slot adjacent to the surface of the pavement; under this condition the top sections of the insert would be restored to perfect top level and thereafter perform in strict accordance with designed behavior.

ICING CONDITIONS

In operation at subfreezing temperatures, the ever-changing relationship of the top surfaces should contribute favorably to breaking the interfacial bond with surface ice. In addition, the insert's susceptibility to vertical load flexure when broadly spanned similarly could cause it to function like the de-icing element on the leading edge of an airplane wing. Continuous fill of the surface portion of the joint is most significant, especially in contrast to sealants which withdraw measurably, since no formation of ice can wedge between the spallable abutments.

MATERIALS

The omission of definitive identification of elastomeric compositions stems neither from neglect nor from lack of acquaintance with such materials. Following the original thesis, this paper covers the development of mechanical concepts applicable to the subject purpose and shows how compositions of widely differing specification may be utilized effectively in the sealing of joints in concrete. These concepts must be executed in materials suited to the demands of a particular design and to the service requirements to which they will be subjected. Their success, therefore, is dependent on intelligent choice and engineering design, and their limitations are inherent in the selected materials.

CONCLUSION

The evolution of compressible insert design as herein developed from the beginning prototype to the butterfly has been a challenging experience. Although I consider the deep contoured insert a significant accomplishment—the validity of which may be attested by the fact that this design could be operable if fabricated totally in spring metal--I do not propose that further development of these concepts should be unanticipated; nor do I wish to imply that the task is hereby completed, when in fact it is little more than begun.

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Effects of Specimen Length on Laboratory Behavior of Sealants

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To provide the maximum degree of predictability of a product, the laboratory testing environment should approach service conditions as closely as practicable. Current practice in the testing of sealants is to use a 2-in. long specimen. However, a sealant in use may be as long as 40 ft. Specimen lengths of 2, 4, and 6 in. are used to show variation in test results with length.

Assuming the sealant to be a perfectly elastic material, stresses in the sealant are computed mathematically. Experimental values of specimens with end neckdown are used. Values of modulus and ultimate strain are measured. A qualitative evaluation of the sealant stresses is shown by photoelastic pictures.

•THE PURPOSE of laboratory testing of any part or product is to predict its behavior in service. Literally millions of dollars have been spent in the effort to make the laboratory test simulate field conditions as closely as possible.

To some extent, this trend is also found in the sealants field. There are some fine environmental testing facilities which control the many parameters involved in sealant testing, such as temperature, humidity, and rate of extension. However, there is one aspect of sealant testing which remains somewhat unrealistic.

STATEMENT OF THE PROBLEM

An actual section of sealant in a pavement joint may have cross-section dimensions on the order of 1 by 1 in., but the sealant strip may extend across two or three lanes of traffic and be as long as 30 or 40 ft in a transverse joint. If the laboratory test is to predict the field behavior, the size and shape of the test specimen should conform as closely as practicable to the field conditions.

The current practice in the testing of sealants is to use a 2-in. long specimen. Much has been said about the shape factor and the neckdown of sealants under a tensile load. However, a short specimen of sealant material is a three-dimensional entity and when a specimen is extended in one direction, both of the other dimensions will change. The sealant specimen will neckdown in its longitudinal dimension, as well as in the vertical transverse direction. On the other hand, the sealant in the actual joint is a length dimension perhaps 400 times as large as the cross-section dimensions, so that the neckdown in this direction is virtually zero.

In the original derivation of the shape factor, Tons (1) assumed a constant volume sealant and also assumed no neckdown in the longitudinal dimension, so that all change in shape was in the vertical transverse direction. It is true, therefore, that the short, 2-in. specimen is not consistent with the basic conditions on which the shape factor derivation is based.

Paper sponsored by Committee on Sealants and Fillers for Joints and Cracks in Pavements and presented at the 44th Annual Meeting.

THEORY

How long, then, should a sealant specimen be? This question may perhaps best be answered by examining the end points to determine the limits of the problem and then comparing the results of actual test specimens with these end points to determine a practical specimen size. The end points might be defined as follows: (a) a unit cube of material which, when extended in one direction is completely free to deform in its other two dimensions, and (b) a specimen with a square cross-section but an infinite length in its third dimension.

If the sealant is considered a perfectly elastic material, the internal work of deformation according to Treloar's (2) kinetic theory is expressed as:

$$W = 1/2\, G\left(\lambda_1^2 + \lambda_2^2 + \lambda_3^2 - 3\right) \tag{1}$$

in which G is shear modulus, and λ is ratio of extended length to the original dimension, in each of three directions. The external work done by the applied forces is

$$dW = f_1\, d\lambda_1 + f_2\, d\lambda_2 + f_3\, d\lambda_3 \tag{2}$$

Differentiating the internal work expression and equating it to the external work expression yields a set of simultaneous equations:

$$\begin{aligned} \lambda_1 f_1 - \lambda_3 f_3 &= G\left(\lambda_1^2 - \lambda_3^2\right) \\ \lambda_2 f_2 - \lambda_3 f_3 &= G\left(\lambda_2^2 - \lambda_3^2\right) \end{aligned} \tag{3}$$

In the unit cube specimen, the only work done is in the tensile (λ_1) direction so that the external work expression reduces to

$$dW = f_1\, d\lambda_1 \tag{4}$$

In a unit section (or free body) cut from the infinite length specimen, there must exist a stress in the longitudinal (λ_3) direction to hold the dimension in this direction constant. The external work expression, therefore, contains both λ_1 and λ_3 terms.

In the unit cube specimen, since the sealant undergoes no change in volume, the following relationship must hold true:

$$\lambda_1\, \lambda_2\, \lambda_3 = 1 \tag{5}$$

Therefore, for this specimen under simple elongation, the extension ratios are $\lambda_1 = \lambda$, $\lambda_2 = 1/\sqrt{\lambda}$, and $\lambda_3 = 1/\sqrt{\lambda}$.

Since the only external force acting is in the tensile (λ_1) direction, the stress reduces to

$$f = \frac{dW}{d\lambda} = G\left(\lambda - \frac{1}{\lambda^2}\right) \tag{6}$$

Using for comparison an extension of 100 percent and a shear modulus of 10 psi, this stress becomes $f = 10\ (2 - 1/4) = 17.5$ psi.

For the unit free body cut from the infinite length specimen, the simultaneous equations must be used. The extension ratios for this case are $\lambda_1 = \lambda$, $\lambda_2 = 1/\lambda$, and $\lambda_3 = 1$. The simultaneous equations reduce to:

$$\begin{aligned} 2\ f_1 - f_3 &= G\,(4 - 1) \\ - f_3 &= G\,(1/4 - 1) \end{aligned} \qquad (7)$$

so that $f_1 = 1.875$, $G = 18.75$ psi; and $f_3 = 0.75$, $G = 7.5$ psi. Combining these two values gives a principal stress in the sealant, $f = 22.3$ psi. This value is 21.5 percent higher than the unit cube specimen. It is important to note that the stress in the λ_1 direction varies by only about 6 percent.

With these two end points which are 21 percent apart as a basis for comparison, it is to be expected that the experimental results would fall within this range. The shorter specimens should approach the lower limit (17.5 psi) and the longer specimens should show a principal stress approaching the upper limit (22.3 psi).

EXPERIMENTAL WORK

The experimental work was performed with 2-, 4-, and 6-in. long specimens. Cross-sections dimensions of the specimens were 3/4 by 1 1/2 in. The material used was a gray, two-component pourable polysulfide sealant. The specimens were extended 100 percent and the neckdown in the longitudinal (λ_3) direction was measured with a micrometer depth gage. Transverse (λ_2) neckdown values were computed from the constant volume relationship. Table 1 includes both the experimental data and the solution of the equations for the values of stress in the specimen. Each value of experimental data represents the average of four specimens. The percent variation given is the variation from the upper limit which is considered to be the true value. The values indicate that the very short (2-in.) specimens give the same value, 17.5 psi, as the unrestrained cube. A quick extrapolation of the tabular results would indicate that a specimen 10 or 12 in. long would give results within 5 percent of the upper limit values. However, much of the testing equipment currently in use may not be able to handle such long specimens.

Figure 1 shows strain patterns on sealant specimens in 2-, 4-, and 6-in. lengths. Lines are scribed on the specimens at 1/4-in. spacing. In the 6-in. specimen the lines are curved for about 1 1/2 in. in from each end of the specimen. This leaves 50 percent of the specimen undisturbed by end effects. On the other hand, the curved lines on the 2-in. specimen indicate that this piece is dominated by the effect of the end neckdown.

TABLE 1

Specimen Length (in.)	Extension (%)	Longitudinal Neckdown (in.)	λ_1	λ_2	λ_3	f_1 (psi)	f_3 (psi)	Principal Stress (psi)	Variation (%)
2	100	0.29	2.0	0.714	0.7	17.4	0.3	17.5	21.5
4	100	0.30	2.0	0.588	0.85	18.3	4.4	19.2	13.9
6	100	0.32	2.0	0.555	0.90	18.4	5.55	19.9	10.5

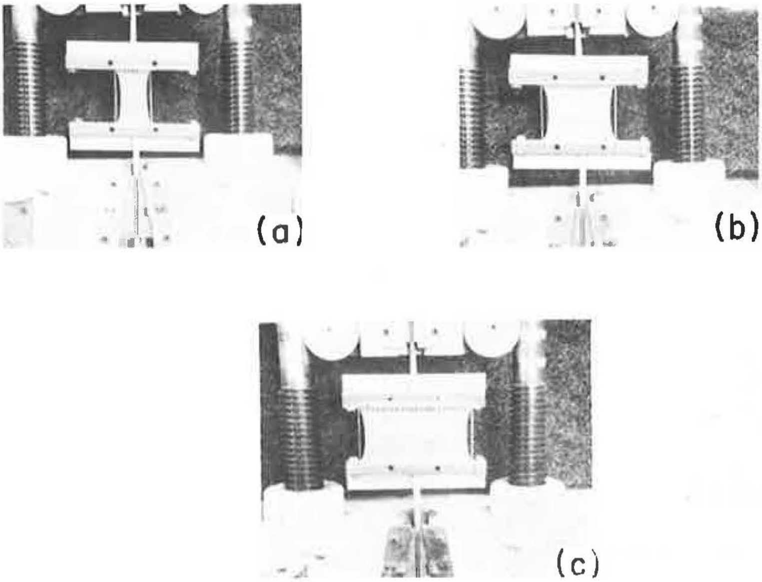

Figure 1. Marked specimens strained 100 percent: (a) 2-in. specimen, (b) 4-in. specimen, and (c) 6-in. specimen.

The photoelastic pictures (Fig. 2) bear out the results shown by Figure 1. These photoelastic pictures must also be considered as only qualitative, principally because of the rapid stress-relaxation rate of the translucent specimens.

Tests of ultimate strain and modulus of elasticity were also conducted in the experimental phase of this work. The results of these tests are shown in Table 2. There is practically no difference in the values of modulus or ultimate strain for the different size specimens tested. This appears to be consistent with the small variation in the stress in the f_1 direction (Table 1) since the stress in this direction is the value recorded by the testing machine.

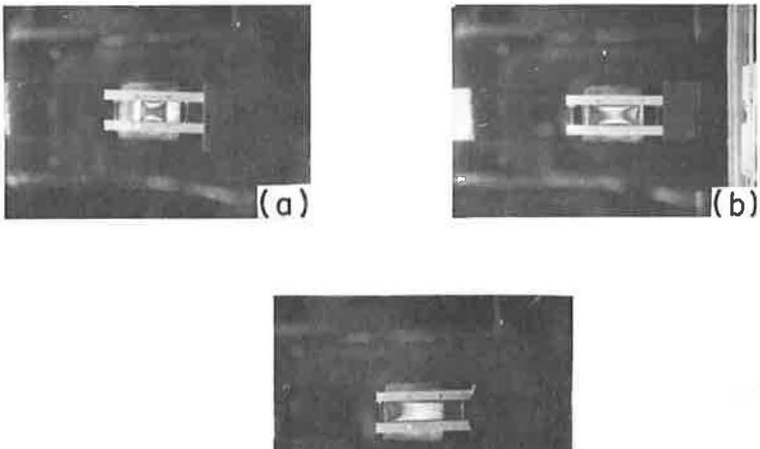

Figure 2. Patterns of stress in sealant specimens at 25 percent elongation: (a) 2-in. specimen, (b) 4-in. specimen, and (c) one-half length of 6-in. specimen.

TABLE 2

Specimen Length (in.)	Load (lb)	Gross Area (sq in.)	f_1 (psi)	Necked-Down Area (sq in.)	t_1 (psi)	Mod. of Elasticity (psi)
2	49	1.5	33	0.75	66	15
4	101	3.0	34	1.5	68	15.3
6	152	4.5	34	2.24	68	15.6

CONCLUSIONS

Intuition would seem to indicate that a longer sealant specimen would be more representative of actual use conditions than the extremely short specimen. The calculations included here indicate that the 2-in. specimen shows stresses that are 25 percent low. An increase of length of the specimen to 6 in. would reduce this error to approximately 10 percent. A specimen length greater than 6 in. would reduce the error still further, but testing equipment size would make the specimens very difficult, if not impossible, to handle. It is also true that the gain in accuracy beyond this point is subject to question because of the scatter in experimental data.

Pictures of the marked and strained specimens indicate that the 6-in. specimen has a central portion of 50 percent of the specimen length which is undisturbed by the effects of end neckdown. Photoelastic pictures appear to bear out this statement.

It is difficult to draw any conclusion from the results of modulus and ultimate strain tests. A first glance would indicate that the results are completely independent of specimen length. However, the stress indicated by these tests is in the direction of the applied load only.

It is recommended that the longer specimen be used whenever possible in testing work, since it appears to give results more representative of field conditions.

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Performance of a Compression Joint Seal

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•FREQUENT EARLY failure of common dowel load transfer devices and jointing systems due primarily to corrosion and the entry of free water into joint openings in concrete pavements led a producer of these devices into the research which resulted in the development of a preformed compartmented polychloroprene compression joint seal.

Wide variations in pavement and bridge deck design, joint forming practice, climatic behavior, materials and methods of construction, and what appears to be a general lack of understanding of the forces at work in a typical road or bridge joint environment have given rise to a wide variety of ineffective sealing materials, most of which are of a stress reversing type. Most of these sealants have been effective for only relatively short periods of time, depending on the service conditions imposed.

The idea of a compression joint seal utilizing a material with a demonstrated long outdoor service capability will come to anyone who has examined the sealing problem at length. Recent comprehensive field tests in a number of states incorporating a wide range of liquid and preformed sealers have tended to indicate a good performance capability for compression joint seals (1, 2, 3).

CRITERIA FOR A COMPRESSION JOINT SEAL

An unsealed, jointed pavement has a built-in potential to destroy itself early in its design life. Any attempt to identify a typical kind of pavement distress as being related in part at least to a sealant failure and any discussion of sealing practices would be incomplete without first attempting to define the purpose of a joint seal. Photographs taken at random from recently completed portions of the Interstate Highway System seem to lay down criteria for the performance of any seal, preformed compression or otherwise (Figs. 1-6).

An examination of typical pavement distress indicates the following design criteria for a compression joint seal:

1. It must have a movement capability consistent with volume and temperature changes peculiar to a specific pavement design and environment.
2. It must seal out the entry of free water and, if possible, channel it off the pavement as quickly as possible.
3. It must seal out the entry of incompressibles from the top and sides of the pavement.
4. It must exert a compressive force against and maintain contact with the inner faces of the joint during extremes of slab movement.
5. It must absorb the expansion movement within itself without being extruded above, or expelled from, the joint opening.
6. It must be rugged enough under any condition of slab movement to withstand forces inherent to repetitive traffic loadings, as well as the downward forces exerted through snow, slush, maintenance materials and incompressibles.
7. It must be capable of performance in extremes of hot and cold weather.
8. Because of the difficulty of getting joints "surgery room clean" in the field, its performance should not be entirely dependent on ability to maintain bond to concrete.
9. It must have a long outdoor service capability and be relatively unaffected by sunlight, ozone, petroleum products, chlorides, soil bacteria, maintenance chemicals,

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Paper sponsored by Committee on Sealants and Fillers for Joints and Cracks in Pavements and presented at the 44th Annual Meeting.

Figure 1. Complete structural failure on a 7-yr-old turnpike.

Figure 2. Dowels locked in corrosion with movement coming midslab on a 6-yr-old turnpike.

Figure 3. Off-center longitudinal breaking on a 3-yr-old Interstate highway.

Figure 4. Crushing tends to come first at juncture of transverse and longitudinal joints.

Figure 5. Repeated resealing.

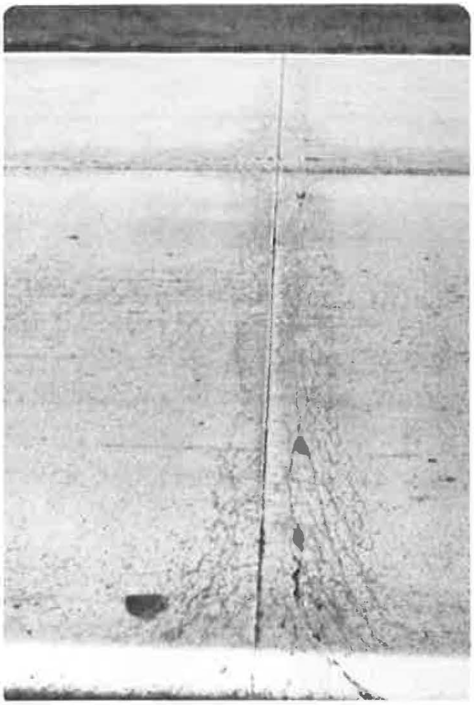


Figure 6. Premature crushing on 6-yr-old turnpike.

cement alkalis, extremes of hot and cold temperatures, forces of abrasion and compressive strains of long-term duration.

COMPRESSION SEAL THEORY

The compression seal discussed in this paper is a preformed tubular compartmented elastomeric device of a given width. It is inserted between two slabs and must constantly maintain a compressive force against the joint interfaces. For all practical purposes, the width of the seal to be used in a given joint opening is computed by adding the anticipated change in joint width to the as-constructed joint width plus a small width safety factor.

SHAPE OF SEAL

Experiments with numerous differing internal web configurations in an attempt to obtain the maximum residual compressive forces against the inner jointfaces under all stages of joint movement have resulted in a general standardization on the cross-braced webs shown in Figures 7 and 8.

The requirement for the seal to deform within itself partly dictates the angle of the web bracing; however, the necessity for a maximum amount of compressive push is best achieved by diagonal bracing rather than round webs, chevron webs or other similar variations. Figures 7 and 8 illustrate our best efforts to date for sealants ranging from $\frac{1}{4}$ to 1 in. in width for contraction joints, $1\frac{1}{4}$ to 2 in. for expansion joints, and $1\frac{3}{4}$ to 6 in. heavy duty bridge seal configurations. Although these seal shapes can probably still be improved, they represent a great deal of trial and error in the field and numerous shape changes as dictated from field usage. A set of working tolerances had to be arrived at due to the continual variances in outer dimension and web thickness natural to the extrusion process. Again, these have been decided on after millions of feet of production (Fig. 9).

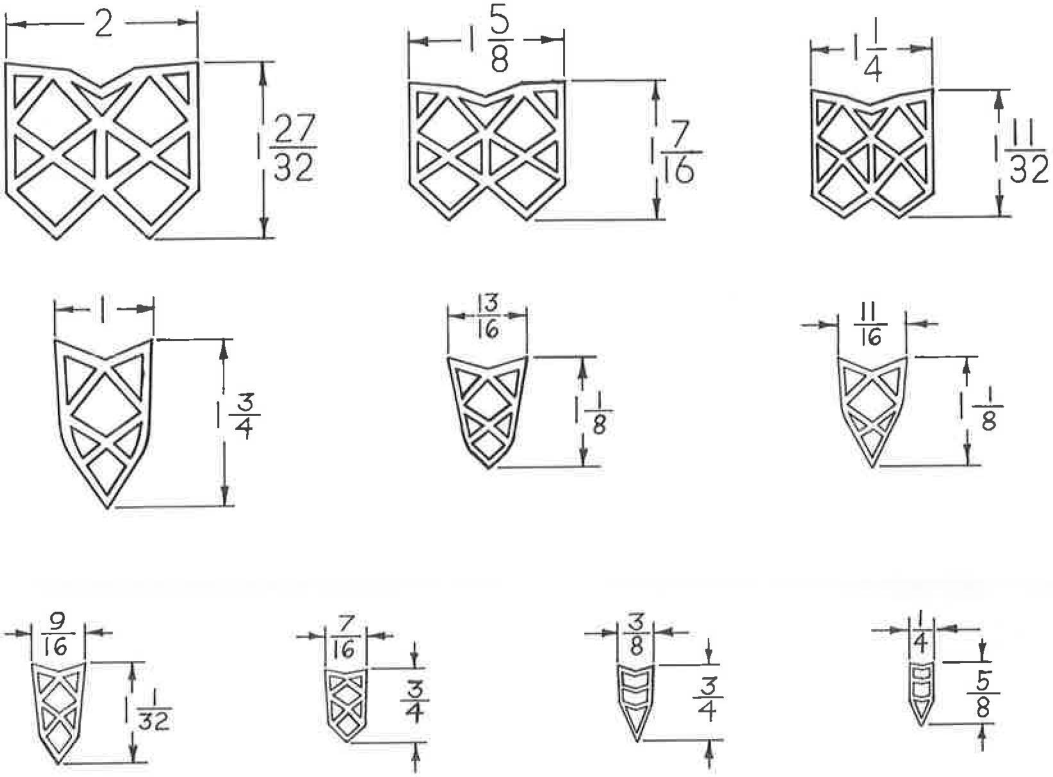
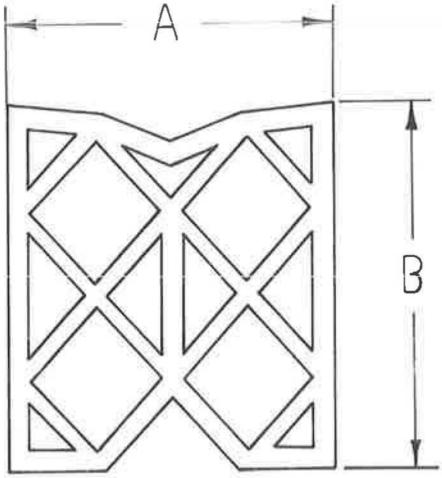
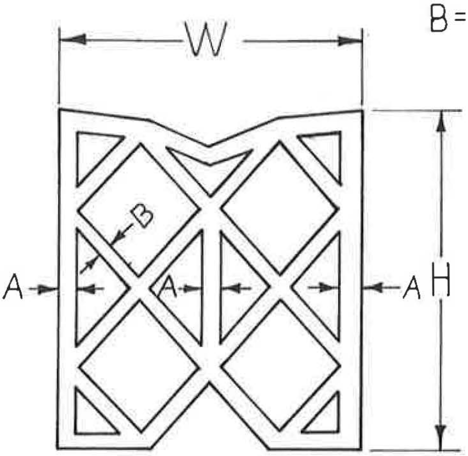


Figure 7. Typical seal designs.



DIM. A	DIM. B
1¾	2
2	2 1/16
2½	2¾
3	3 13/32
4	4 23/32
5	6
6	7 1/16

Figure 8. Typical bridge seal designs.



A = SHELL
B = INTERNAL WEBS

WIDTH	HEIGHT	THICKNESS	
		A	B
$1\frac{3}{4}{}^{+3/16}_{-0}$	$2\pm\frac{1}{8}$	$\frac{1}{8}{}^{+1/32}_{-1/64}$	$\frac{3}{32}{}^{+1/64}_{-1/32}$
$2{}^{+3/16}_{-0}$	$2\frac{1}{16}{}^{+}_{-}\frac{1}{8}$	$\frac{1}{8}{}^{+1/32}_{-1/64}$	$\frac{3}{32}{}^{+1/32}_{-1/64}$
$2\frac{1}{2}{}^{+1/4}_{-0}$	$2\frac{3}{4}{}^{+}_{-}\frac{1}{8}$	$\frac{3}{16}{}^{+3/64}_{-1/64}$	$\frac{3}{32}{}^{+1/32}_{-1/64}$
$3{}^{+1/4}_{-0}$	$3\frac{13}{32}{}^{+}_{-}\frac{3}{16}$	$\frac{3}{16}{}^{+3/64}_{-1/64}$	$\frac{1}{8}{}^{+3/64}_{-1/64}$
$4{}^{+5/16}_{-0}$	$4\frac{23}{32}{}^{+}_{-}\frac{1}{4}$	$\frac{1}{4}{}^{+3/64}_{-1/32}$	$\frac{3}{16}{}^{+3/64}_{-1/64}$

Figure 9. Typical seal tolerances.

The importance of internal web design to seal performance was proven conclusively in the New York State Delmar Bypass tests. Two variations of chevron-type webs were utilized and both failed very quickly because they lacked the necessary compression during cold weather and were driven to the bottom of the joint grooves. Our experiments with a wide variety of internal web designs indicate that there may not be a great deal of latitude in this field. The absolute necessity for 3- to 4-yr field performance tests to prove the feasibility of different web designs has also tended to result in the standardization of webs shown in Figures 7 and 8.

LUBRICANT ADHESIVE

Our design team expended considerable effort in the field to develop a material in liquid form that could be used as a lubricant adhesive for a compression joint seal. It would be difficult, if not impossible to insert a typical compression seal into a groove without some type of lubricant. Some of the earliest installations were made with oil soap. However, it was felt that some liquid that was easily field applied in a single-component system and contained a high degree of lubrication when applied to concrete in extremes of hot and cold weather would give better performance. Many adhesives, both emulsions and solvent based, were experimented with. The resultant adhesive was selected for its long-term compatibility with neoprene, being a neoprene-based adhesive.

A priming agent is absolutely mandatory in any serious attempt to seal a joint with compression seals so that it is completely leakproof. Any existing capillary system in the surface of concrete, porosity, minor spalls, and cavitation inherent to joint sawing and the blasting effects of sawing slush must be primed out with a durable material. A neoprene adhesive compound seems to be ideally suited for this mission. Obviously, neither oils nor soaps would be practical as a priming agent.

The natural notch sensitivity of synthetic rubbers when compressed, or in effect stretched, also presents a problem during installation. The tendency of some aggregates to saw out, leaving sharp edges, and forcing of the neoprene tubes into narrow grooves can produce ragging, cutting and tearing. A thick slippery rubbery lubricant is indicated and the additional ability to seal any tears or minor cuts incurred in the installing process is, of course, highly desirable.

Undoubtedly, it is desirable to bond these neoprene tubes to the surface of the concrete. However, the practical difficulties of field cleaning concrete joints need no further elaboration in this report. Ability to bond to concrete is related to ability to clean properly and maintain cleanliness of joints before application. It may not be practical to expect a typical contractor to observe "surgery room" cleanliness in the field. Our design team felt that we will take whatever bond we get with this neoprene adhesive, regardless of degree, realizing that if the neoprene tubes are always in some degree of compression, the adhesive will never be called on to perform in tension.

Excess adhesive tends to be squeezed downward during insertion of the seal in the grooves. This excess will cure out in a type of "shear shelf" that helps prevent the seals from migrating downward. In colder weather, when the slabs are in a contracted state, residual compression in the seal is somewhat less and the rubber is somewhat less flexible. Hence, anything that will give bottom support to the seal is, of course, desirable.

Some observers have exhibited disappointment with the adhesive properties of the lubricant adhesive because they can in some cases pull out the bonded seals. After considerable experimentation with different types of adhesives, it was realized that the action of pulling on a piece of resilient rubber places these tubes in a very severe test of tear and peal in addition to stretch which reduces the cross-section of the tube. The service requirements of these seals are in no way related to the aforementioned test. Most of the forces in service are in a downward direction and it has been an extreme rarity after observing millions of feet in service to see a seal migrate upwards.

SELECTION OF POLYCHLOROPRENE (NEOPRENE)

An examination of the properties of known low-cost synthetic rubbers with respect to resistance to compression set, ozone, aging, sunlight and weathering, abrasion, chunking or gouging, oils and chemicals and temperature extremes seemed to point in the direction of polychloroprene (neoprene). Most other synthetic rubbers seem to be deficient in one of the important properties. However, the outstanding performance of neoprene in resistance to compression set for long-term exposures was the predominating property which resulted in its use. The attached specification (Appendix A) gives a description of the properties and testing methods that appear to be adequate for performance of a compression joint seal for most environments.

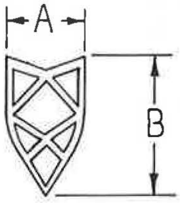
SLAB MOVEMENT

It is readily apparent that the degree of slab movement or joint width change must be known or estimated before the appropriate seal can be selected for a given joint. Although the only true measurement of the overall range of joint width change is that of actual measurement itself, a rule of thumb follows: (a) 1/16 in. for each 10 ft of slab length on pavement slabs on grade, and (b) 1/8 in. for each 10 ft of slab length on bridge decks. The difference seems to be related to the presence or lack of subgrade or mechanical restraint.

Short of actual measurement of joint width change, calculations of anticipated changes should be made for bridge decks to avoid exceeding compression limits for specific cross-sections and to use the most economical size of seal. Appendix B shows typical computations for deck lengths of 80, 125 and 150 ft at an as-constructed temperature of 70 F.

The overall movement potential of contraction joints is considerably affected by temperatures prevailing at the time of placement of the concrete. Hot weather poured slabs move a greater distance in contraction than cool weather poured slabs. In the early period of development in New York State, a 9/16-in. wide seal in a 3/8-in. wide contraction joint was considered to be adequate for 61-ft long slabs poured in cool weather; however, it later proved that a 13/16-in. width for the same size joint opening was necessary to handle the increase movement in contraction of the hot poured slabs. It is important to keep this in mind when measuring typical volume changes to determine the appropriate seal size.

Evidence exists that there is a limit to movement of very long pavement slabs or continuously reinforced pavements. It has been observed that the prestressed pavement at Biggs Air Force Base built in 500-ft long panels has an overall change in joint width of



SEAL SIZE		SLAB LENGTH					GROOVE		TYPE OF JOINT
A	B	20	40	60	80	100	WIDTH	HEIGHT	
7/16	3/4	■					1/4	1 1/4	LONG.& TRANSV.
9/16	1 1/32		■				1/4	1 1/2	TRANSVERSE
11/16	1 1/8			■			1/4	1 1/2	" "
13/16	1 1/8			■			3/8	2	" "
13/16	1 3/8			■			3/8	1 3/4	" "
1	1 3/4				■		1/2	2 1/2	" "
1 1/4	1 11/32			■			3/4	2	EXPANSION
1 5/8	1 7/16			■	■		1	2	" "

Figure 10. Seal and groove size recommendations for pavements.

about 1 in. Most of the continuously reinforced pavements, regardless of length, have reported changes in joint width of approximately 1 in., obviously due to a buildup of mechanical or subgrade restraint.

Although it is extremely difficult to predict with accuracy the movement of slabs, the seal sizes given in Figure 10 worked well for the pavement slab lengths indicated when there was no flagrant unloading or movement problem.

It is considered at this time that other factors capable of affecting changes in slab length in pavements, such as drying shrinkage and end rotation attributable to warping, are insufficient to affect seal performance if the recommended seal sizes for given typical slab lengths are observed.

UNLOADING OF JOINT MOVEMENT

The problem of unloading of joint movement is more critical in some areas than in others due to general design and prevalent construction practice. Unloading occurs when there is restraint to slab movement sufficient to overcome the natural desire of a slab to move or change its length. It is a phenomenon wherein two, three, or more slabs move as a single unit, thereby greatly compounding the overall change in width at one particular joint. It is common in pavements of relatively short length (15 to 25 ft) for a short period after placement but normally begins to level off to even movement after the first year, or certainly by the second.

The most serious type of unloading, however, is caused by restraint from the common dowel-type load transfer devices. Crookedness or lack of perfect alignment of dowels is probably the greatest early cause of unloading. Salt brine entering the joints triples the speed of corrosion, as does the typical repeated action of complete stress reversal from repetitive traffic loading. The dowels seize in their sockets and lock as does a corroded nut and bolt. Unloading apparently is inevitable where common dowels are used and complicates the performance not only of liquid sealants with limited movement capability, but also of the compression seal.

On pavement slabs over 50 ft in length, compression seals are dependent for ease of installation on normal and even volume changes. Considerable difficulty has been encountered in some states in inserting compression seals because of this unloading of movement problem and it has usually been traceable to restraint at the doweled joints. In one instance, a quarter of a mile of pavement exhibited extreme seal refusal tendencies because the joint sawing crews had completely missed the load transfer devices with their saw cuts and the movement was coming in the form of midslab cracks. The excellent performance of compression seals recorded in New York State has occurred while utilizing the new "restraint free" load transfer devices.

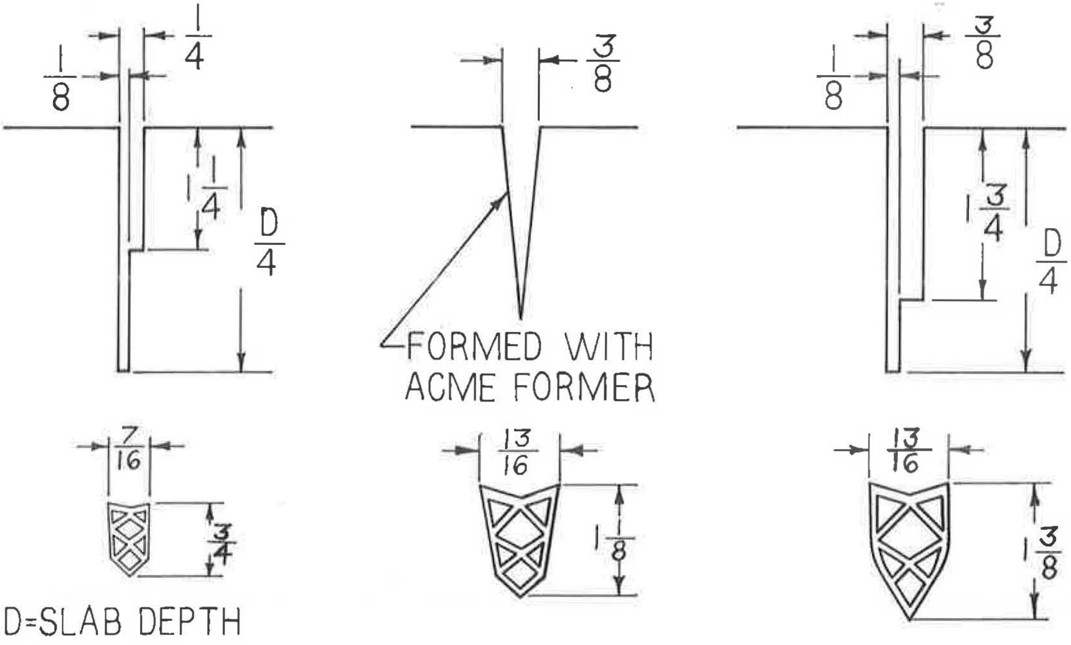


Figure 11. Typical grooves and seal shapes.

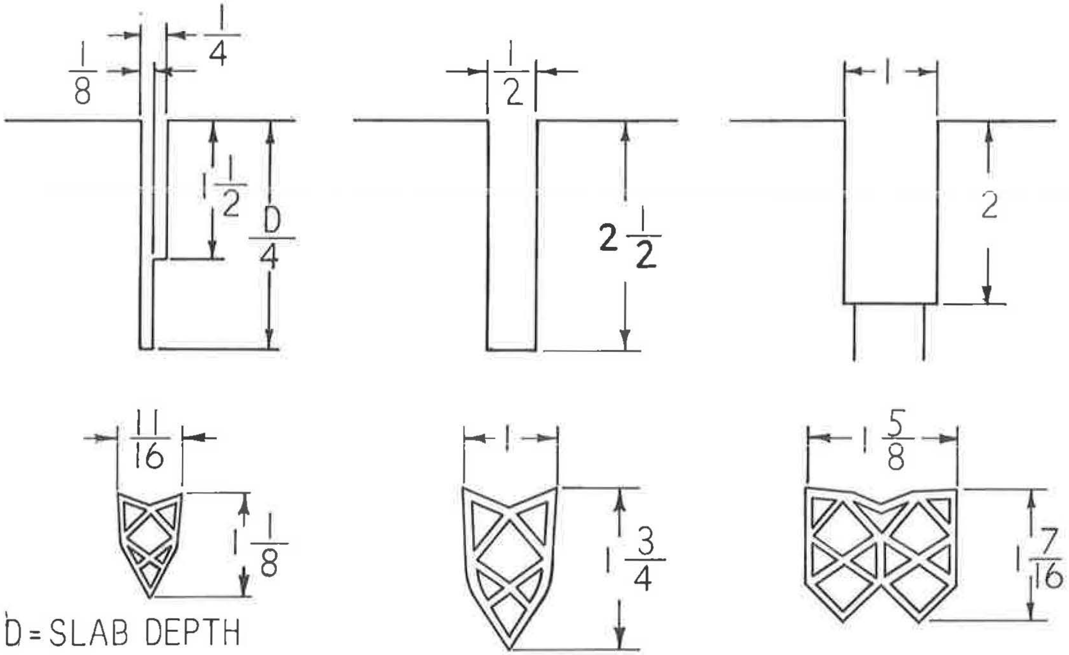
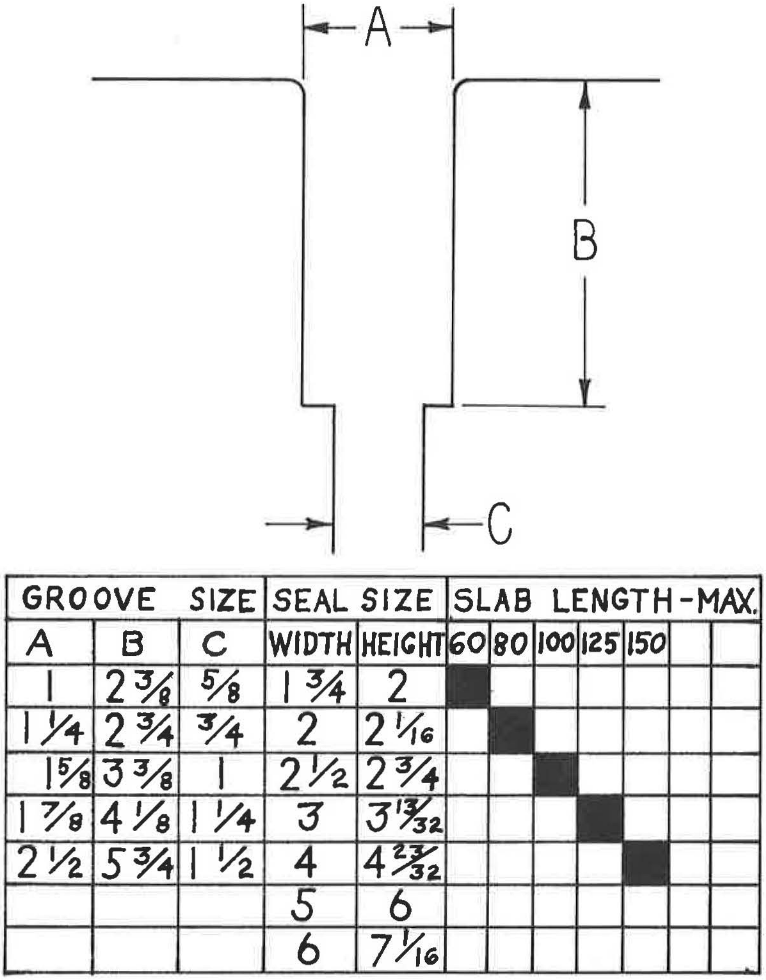


Figure 12. Typical grooves and seal shapes.

Load transfer devices must be initially and potentially free of restraint to obtain full efficiency of preformed compression joint seals. Wherever they have been used, compression seals have tended to indicate if the slabs were having normal movement.

JOINT SHAPE CRITICAL FOR OPTIMUM SEAL PERFORMANCE

A definite and uniform shape for a given joint is not only critical for sealants installed in liquid form but also for a compression seal, although for completely different reasons. The preformed seal is essentially a resilient compartmented synthetic rubber tube, always under compression. At the point of maximum joint opening, the compressive forces exerted against the joint faces are considerably less than when the joints are in a state of closure. A noticeable tendency exists for traffic to drive the seals downward, particularly on slabs over 60 ft in length and where unloading is present. The seals can migrate downward to the bottom of the joint groove and although there is little likelihood of serious crushing damage to slab ends from incompressibles, this is an undesirable position for the seal. It became readily apparent that a seal seat or stop should be a mandatory requirement for all seals in all types of joints, regardless of slab length or joint width. Either a wedge-shaped groove as indicated in Fig-



GROOVE SIZE			SEAL SIZE		SLAB LENGTH-MAX.						
A	B	C	WIDTH	HEIGHT	60	80	100	125	150		
1	2 3/8	5/8	1 3/4	2	■						
1 1/4	2 3/4	3/4	2	2 1/16		■					
1 5/8	3 3/8	1	2 1/2	2 3/4			■				
1 7/8	4 1/8	1 1/4	3	3 13/32				■			
2 1/2	5 3/4	1 1/2	4	4 23/32					■		
			5	6							
			6	7 1/16							

Figure 13. Seal and groove size recommendations for bridges.

ure 11 or a step saw cut is the recommended shape. The depth of the seat or stop is varied to fit the compressed vertical height of the seal (Figs. 11, 12, and 13).

GOOD JOINTS NECESSARY FOR COMPRESSION SEALING

Wherever compression joint seals are in use, there has been a marked tendency on the part of constructors to clean up or improve their jointing practices. All spalls must be patched before inserting compression seals and the end result has been a self-inspection service at the joints for a state highway department.

SELECT FIT OF SEAL AND JOINT SHAPES NECESSARY

For optimum performance, seal shapes should reflect or properly mate with the joint shape (Figs. 11, 12, and 13). Side pressure of the seal against the inner joint faces should be maintained at all times over substantial areas. It is also highly desirable to have good, straight, smooth joint faces, as well as smooth surfaced seals free of lines, depressions and die streaks.

PROPER SETTING HEIGHT

In the early installation of these seals, setting height was specified at from $^1/_{16}$ to $^1/_8$ in. below the riding surface of the pavement. Because of a tendency of joint edges to wear down under repetitive traffic loadings and from the abrasive action of maintenance grits, it is now felt after observing evidence of wear and snow plow damage, it is better to set the seals at least $^1/_4$ in. below the riding surface. Snow plows traveling at high speeds and small stones caught beneath the plow blade edge can rag out the top compartments. Since neoprene has a long life expectancy, the seals should be set lower in the joint grooves to anticipate the minor edge raveling that inevitably comes to nonradius edge joints.

SEAL "POP"

The typical compression seal configuration is a difficult extrusion at best. Some of the earlier extruded shapes had a noticeable tendency to tuck into themselves rather than into the joint grooves. Side friction and excess cavitation from joint faces may cause certain shapes of seals to tuck partially into themselves rather than fully into the joint groove. Subsequently, the first sizeable movement of the slabs in contraction tends to release the seal and it "pops" up to its full height, giving the impression that the seal is popping out of the joint where, in fact, it actually never was fully inserted. Consequently, all original cross-sections were redesigned to eliminate as far as possible the tendency to pop. Bent rather than straight webs, round edges and an outside shape lacking basic insertability have serious pop potential.

The seal shapes shown in Figures 7 and 18 have all been relieved of pop tendency. A slight taper on smaller seal sizes seems to be important to insertability.

GROWTH-STRETCH PHENOMENON

The tendency of construction or installing personnel to stretch the smaller sizes of compression seals (under 1 in. wide) during installation has given rise to some concern. One incident was reported wherein a contractor requested information on the tensile strength of the cross-section. It developed that he intended to hook a D8 tractor to the material to stretch it 300 percent and cut his material costs accordingly.

A typical compression seal when being compressed for insertion elongates. The percentage of elongation is directly proportional to the amount of squeezing or compression required for insertion into the joint opening. Constant unavoidable variations in the web thickness of the extruded seals within allowable tolerances can result in more severe squeezing or elongating and, therefore, attempts to arrive at a maximum allowable growth or stretch have been unsuccessful. As an example, a $^1/_4$-in. saw cut as constructed in a 60-ft slab can vary in width as much as $^5/_{16}$ in., depending on temperature at the time of installation. Saw blade wear, differences in joint width due to other variables in construction practice, as-constructed temperature differences, and excessive drying shrinkage are of sufficient magnitude to vary the amount of growth in installation. In one large paving project in 1963, incorporating some 206,000 lin ft of joint, only 170,000 lin ft of seal were used; growth accounted for the difference. Constant close supervision was in effect on this project so that no visible stretching of the seal was involved.

DURABILITY OF JOINT INTERFACES

The durability of joint interfaces is critical to seal performance. If a joint spalls after sealing with any known sealant, the seal can no longer be effective. Spalls have to be patched before a seal can work. Conventional spall patching methods have tended generally to be troublesome and somewhat unreliable. As a companion material, a low-cost energy-absorbing spall patch material was developed in conjunction with this seal. The principle was used that a force or wheel load applied to a stone laying on a hard epoxy-type patch will normally take out the patch at or near the juncture of the patch and the base concrete. Energy-absorbing isopox polymer patches do not fully transmit a wheel load force to the bond between the patch and the concrete and, in fact, tend to absorb the force within itself. Polyethylene plastic dams were developed to fit into the joints to restore the original joint shape when spall patching.

SAWED JOINTS IN ASPHALT

In a recent report to the Highway Research Board (4), the Connecticut State Highway Department reported favorably on their work with relieving asphalt overlays with saw cuts to control reflection cracking. Our early experimentation with sealing of asphalt sawed joints has been largely unsuccessful; however, it is now believed that a proper sealing technique utilizing compression seals can be worked out. The principal difficulties occur during warm days when the asphalt becomes at least partly mobile.

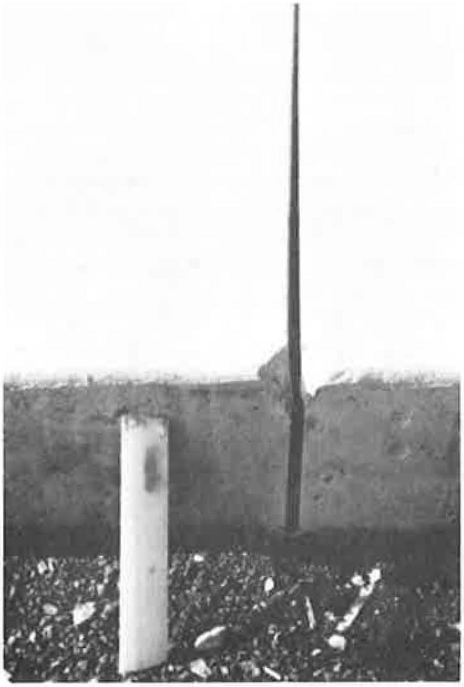


Figure 14. Pavement edge groove forming.

Figure 15. Pavement edge sealing.

The compressive forces tend to mount up the asphalt at the joints. Further experimentation is planned using deeper saw cuts and setting the seals deeper with improved lubricant-adhesive techniques.

PAVEMENT EDGE SEALING

The earliest and most noticeable evidence of crushing effects on pavements can be found at the outside edges, probably due to the presence of shoulder materials which tend to migrate into the joint openings from the sides. A number of areas now using compression seals have incorporated edge sealing into their specifications to check this area of distress.

Edge grooves are formed with short sections of plastic scale inserts placed inside the paving forms. These can be then used as saw point indicators so that a continuous groove is sawed or formed through to the bottoms of the outside edges of the pavement. Michigan and the Ontario Department of Highways have incorporated baseplates under their load transfer devices which, with the compression seals, prevent entry of materials into the joint spaces from all four sides of the pavement (Figs. 14 and 15).

PAVEMENT THRUST AND COMPRESSION SEALING

Cement concrete pavements have historically thrust themselves in the direction of bridges, probably because of incompressibles finding their way into joint openings of pavements during the contraction cycle of movement. As the pavements grow in length during the expansion cycle, they creep or shove towards the bridges or any direction in which they can find relief. The recent predominating use of contraction joints and occasional expansion joints, together with ineffective sealants, will certainly contribute to making the pavement thrust problem a monumental one for maintenance forces (Figs. 16 and 17).

Blowups, bridges pushed off their bearings, split back walls and other evidences of stress relief are common across the country on relatively new pavements of contraction joint design. At one large metropolitan airport, a 1½-mi long runway after 5 yr of life is 2 ft longer, probably due to incompressibles entering the joint openings. Illinois uses four pieces of expansion joint on the last joint before a bridge; Virginia utilizes a special 3-ft wide asphalt-filled trough adjacent to bridges; Maryland build its last panel of pavement adjacent to bridges out of asphalt to delay the effects of pavement thrust.

Figure 16. Split back wall on 10-yr-old bridge.

Figure 17. Crushed bearing seat on a 6-yr-old structure.

It has been the considered opinion of the design group that developed this compression seal that the costly effects of pavement thrust would be greatly minimized, if not eliminated, by its use. Pavements constructed with "grower aggregates" which actually permanently increase their length with time could then be dealt with in initial design and the pavement thrust problem would probably be virtually eliminated.

BRIDGE JOINT SEALING

Bridge joints are apparently sealed for somewhat different reasons than concrete pavements:

1. Salt brine corrosion of bridge subdecks and piers under the joints (Figs. 18 and 19);
2. Migration of back slopes (Figs. 20 and 21);
3. Undesirable side effects of free water escaping through joints (Fig. 22);
4. Aesthetics, including staining of the concrete (Fig. 23); and
5. Accumulation of incompressibles, debris, etc. and potential crushing of concrete (Figs. 24 and 25).

Bridge joints and their accompanying width changes are normally of a much greater magnitude than those of pavements. Slab end rotation, skew joint movement peculiarities, compression limitations on each cross-section of compression seal and other complexities of bridges as compared to pavements call for marked differences in sealing practices. Figures 9 and 13 represent an attempt to recommend seal sizes and tolerances for those bridge deck lengths and joint widths shown. To date, we have made no serious attempts to use compression seals on decks in excess of 150 ft.

From evidence in the field, it would appear that some type of armor plating of bridge joints such as shown in Figure 26 is desirable (Fig. 27). This practice tends to eliminate the problem of durability of concrete or asphalt joint edges and when seal seats or

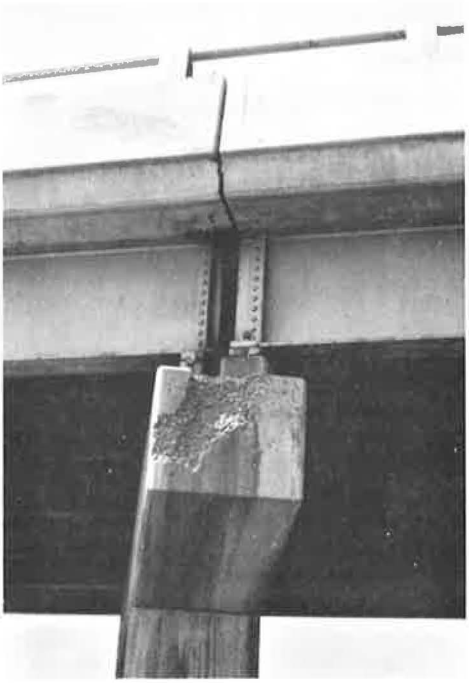


Figure 18. Salt brine corrosion.

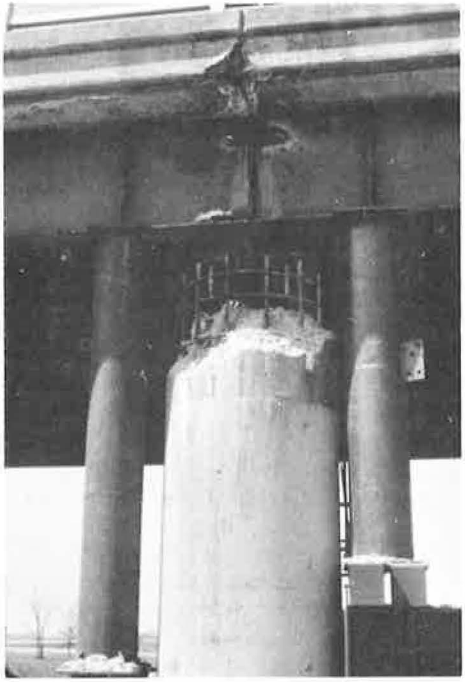


Figure 19. Salt brine corrosion.

Figure 20. Migration of back slope.

Figure 22. Undesirable side effects of free water escaping through joints.

stops are incorporated in the inner joint faces, movement unloading and setting height difficulties are of less concern. Figures 28 and 29 show a practical method of armor plating joints on bridge decks with asphalt wearing courses, heretofore considered to be unsealable.

Bridge compression seals as shown in Figure 8 are much more rugged in cross-section than are those of pavements and

Figure 21. Migration of back slope.

Figure 23. Straining of concrete.

Figure 24. Accumulations of incompressibles, "elephant earing."

Figure 25. Sliding plate joint seal failure.

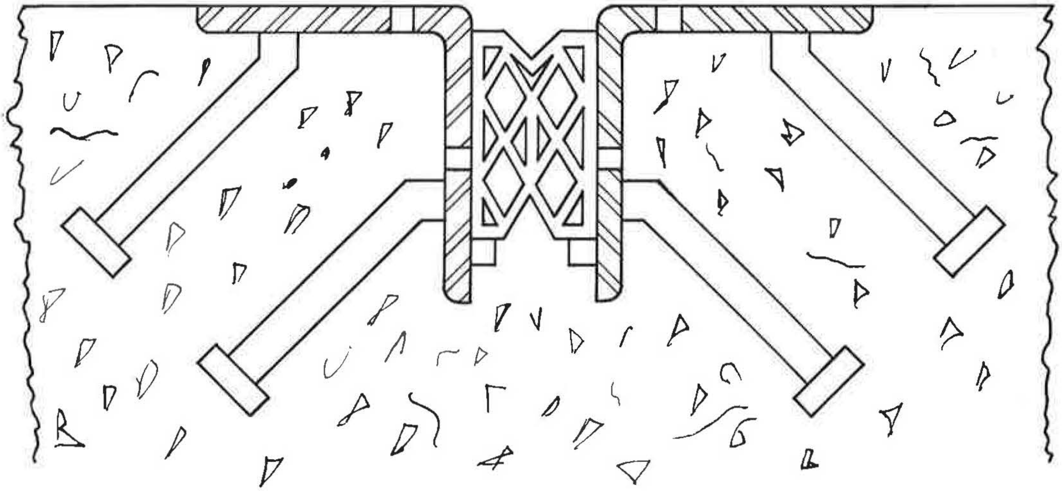


Figure 26. Steel joint faces.

necessarily must be, partly because of the wider joint openings and dynamic movement. One of the reported side effects of the use of these giant-sized bridge seal configurations and the accompanying tremendous compressive force exerted particularly in the expansion cycle of movement is a marked reduction in deck vibration normal to repetitive traffic loadings.

COST OF COMPRESSION SEALING

Over a 3-yr period in New York State, when an alternate of compression seals or two-component polysulfide sealants was permitted, contractors predominately elected to use compression seals. Lack of necessity to purchase expensive complex proportioning and mixing equipment, lack of need for operating engineers, lack of temperature restrictions, no reworking of sealants after the initial installation such as spudding off excess materials in warm weather or filling up joints in cooler weather, no air-entrapment problems, no equipment plug-ups, and the general simplicity of compression sealing became cost factors to contractors in their choice of compression seals. Also, there has not been any reflection in bid prices when compression sealing was subsequently made mandatory in New York State construction.

There are, in fact, other highly desirable cost-reducing potentials resultant from compression sealing. Generally, narrower joints can be sawed at marked reductions in sawing costs per foot. Because of its simplicity, sealing operations can be worked concurrently with other less efficient operations. In some areas, crews who normally removed curing blankets from concrete pavements now install compression seals as well with no additional labor cost to the contractor. The seals are being installed when the joints are at their cleanest with an additional saving in joint-cleaning costs. With no temperature restrictions, sealing crews can work until snow arrives, enabling contractors to finish their project without having to wait over a winter to seal the joints.

In the past 4 yr, the cost of compression seals has been reduced about 50 percent, primarily because of mass productions. With the rubber industry now gearing up for high-volume usage, it is anticipated that further marked reductions will occur. Certain newer materials are presently under test which, if successful, may offer compression seals at costs per foot comparable to the cheapest asphalt sealants available today.

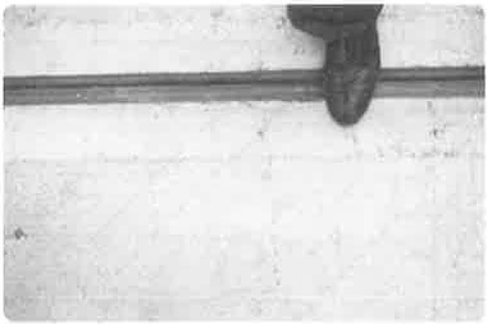


Figure 27. Armor-plated joint with compression seal.

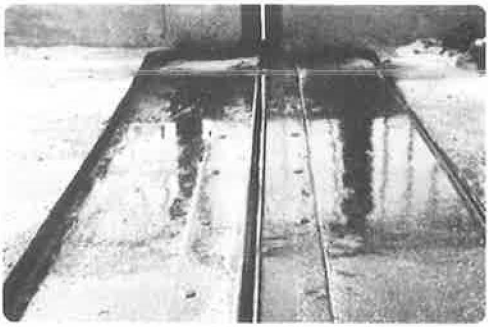


Figure 28. Armor plating of joints in asphalt overlay on a bridge.

Figure 29. Compression seal in armor-plated joint carried through curb.

One cannot view the presently completed portions of the interstate highway system or recently built toll roads without becoming seriously concerned with the frequent evidence of premature pavement self-destruction. There is undoubtedly a definite causal relation between ineffective sealing practice and certain types of premature pavement distress. When the full impact of the real cost of ineffective sealants and the importance of the joint seal as a vital performing component in a pavement is understood and appreciated by design engineers, a realistic appraisal of the cost of sealers that actually seal the joints can be made.

CONCLUSIONS

1. Recent documentation of compression seal performance gives promise of a new device to help extend the maintenance-free life of pavements and bridges.
2. An examination of typical pavement distress has resulted in design criteria for a compression seal.
3. Important considerations in the use of compression seals are the performance capability of the elastomer, outside shape and internal web configuration of the seal, geometry of the joint to be sealed, setting height of the seal with relation to the riding surface, use of a lubricant adhesive, proper sizing technique for each specific pavement design, proper installation, and durability of joint interfaces.
4. A thorough evaluation of the many physical and environmental factors influencing joint width change throughout the overall service life of each particular slab design is necessary for accurate sizing and efficient use of compression seals.

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Appendix A

SPECIFICATION FOR PREFORMED JOINT SEALER

Description

This work includes furnishing and installing preformed elastic joint sealers of the sizes and shapes shown on the plans, or as otherwise permitted by the plans. The sealer shall be installed in the concrete with an approved lubricant adhesive.

Materials

The sealer shall be a preformed, elastic polychloroprene joint sealer, compatible with concrete and resistant to abrasion, oxidation, oils, gasoline, salt, and other materials that may be spilled on or applied to the surface. The sealer shall be so shaped that when installed, at minimum joint opening, it shall be so completely compressed as to be substantially solid and have a minimum of air spaces. It shall also be so shaped that in its compressed condition the top center of the exposed surface shall be depressed below the surface of the installed sealer. The sealer shall be furnished in a sufficient number of widths to accomplish this kind of closure.

The sealer shall conform to the ASTM requirements given in Table 1; it must be compounded using the low crystallizing polychloroprene base. Each lot of the joint seal shall be identified with the manufacturer's name or trademark and shall be accompanied by the manufacturer's affidavit attesting conformance with the specification.

Lubricant Adhesive

The lubricant adhesive shall be a one-component polychloroprene compound containing only soluble phenolic resins blended together with antioxidants and acid acceptors in an aromatic hydrocarbon solvent mixture and shall have the following physical properties:

1. Average net weight per gallon, 7.84 lb ± 5 percent;
2. Solids content, 24 to 26 percent by weight;
3. Brookfield viscosity at 77 F, No. 2 Spindle at 10 rpm, 7,000 to 7,500 cps;
4. The adhesive shall remain fluid from 5 to 120 F; and
5. Film strength (ASTM-D-412), 2,300 minimum tensile strength, 750 percent minimum elongation before breaking.

Test specimens composed of two pieces of 0.064 gage of 6061 aluminum alloy bonded together with the adhesive on a joint 1-in. wide with ½-in. lap and aged 14 days shall show the following minimum strength when tested by the laboratory:

TABLE 1

REQUIREMENTS FOR PREFORMED COMPRESSION SEAL[a]

Property	ASTM Test Procedure	Transverse or Longitudinal Requirement
Tensile strength, min. (psi)	D-412	2,000
Elongation at break, min. (%)	D-412	250
Hardness, Type A durometer	D-676	55 ± 5
Permanent set at break, max. (%)	D-412	10
Compression set, max. (%):	D-395 Method B,	
22 hr/158 F	Paragraph 5 (b)	15
70 hr/212 F		40
Oven aging, 70 hr/212 F:	D-573	
Tensile strength, max. change (%)		-30
Elongation, max. change (%)		-40
Hardness, max. points change		+10
Oil swell, ASTM Oil No. 3, 70 hr/212 F, max. volume change (%)	D-471	80
Ozone resistance, 20% strain, 300 pphm in air, 70 hr/100 F[b]	D-1149	No cracks
Low-temperature stiffening, min. °F to reach 10,000-psi modulus	D-1053	-30

[a] All test sections used in the testing methods shall be cut and buffed from the actual extruded compression joint seal.

[b] Wipe with solvent to remove surface contamination.

1. Dynamic strength, 1,300 psi at 70 and 0 F; and
2. Static (1 min), 700 psi at 70 and 0 F.

Each lot of the adhesive shall be delivered in containers plainly marked with the manufacturer's name or trademark and date of manufacture and shall be accompanied by the manufacturer's affidavit attesting conformance with this specification.

Construction Details

The sealer shall be installed by suitable hand or machine tools and thoroughly secured in place with an approved lubricant adhesive which shall cover both sides of the sealer over the full area in contact with the sides of the concrete joint. The adhesive may be applied to the concrete or the sealer or both. The sealer shall be installed in a substantially fully compressed condition and shall at all times be below the level of the pavement surface by approximately ¼ in. The sealer shall be in one piece for the full width of the transverse joint. In longitudinal joints, the sealer shall be in practical lengths. Any joints in the sealer material shall be adequately sealed with additional adhesive.

The sealer may be installed immediately after the curing period using a lubricant adhesive that is compatible with the sealer and the concrete at that stage. Temperature limitations of the adhesive as guaranteed by the manufacturer shall be observed. Joints shall be cleaned free of foreign material immediately before installation of the sealer.

Inspection of Material

All sealers and adhesives will be furnished to comply with the material as approved as a result of tests. For all such sealer and adhesive furnished and installed on a contract, the contractor shall furnish to the engineer a certification that the materials placed are the same as those approved and shall back this up with a certification by the manufacturer as to the nature and characteristics of the materials purchased by the contractor. The exact details of the certification will be furnished at the time the material under test is approved.

Appendix B

TYPICAL BRIDGE MOVEMENT COMPUTATIONS

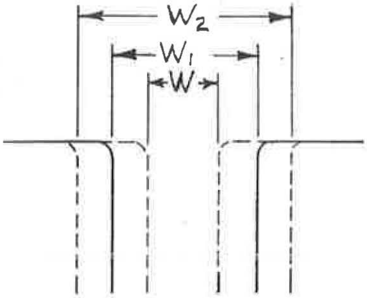
SLAB LENGTH = 80 FEET
POURING TEMPERATURE = 70° F.

α = COEFFICIENT OF EXPANSION
ΔT = CHANGE IN TEMPERATURE
W_1 = GROOVE WIDTH AT 70°F.
W_2 = MAX. GROOVE WIDTH AT -30 F.
W = MIN. GROOVE WIDTH AT 120 F.

L = SLAB LENGTH
ΔL = CHANGE IN LENGTH

T_1 = POURING TEMP. 70°F.
T_2 = MIN. TEMP. -30°F.
T_3 = MAX. TEMP. 120°F.

$$\begin{aligned}\Delta L/10^\circ F. &= L\alpha\Delta T\\ &= 960'' \times (6\times10^{-6}) \times 10^\circ F.\\ &= .0576''\end{aligned}$$



MAX. JOINT WIDTH - W_2

$$\begin{aligned}W_2 &= W_1 + L\alpha\Delta T\\ &= 1.25'' + 960''(6\times10^{-6})(T_1 - T_2)\\ &= 1.25'' + 960''(6\times10^{-6})(70^\circ + 30)\\ &= 1.25'' + .576''\\ &= \underline{\underline{1.826''}}\end{aligned}$$

MIN. JOINT WIDTH - W

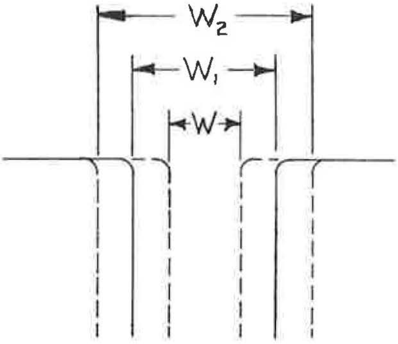
$$\begin{aligned}W &= W_1 - L\alpha\Delta T\\ &= 1.25'' - 960''(6\times10^{-6})(T_3 - T)\\ &= 1.25'' - 960''(6\times10^{-6})(120 - 70)\\ &= 1.25'' - .288''\\ &= \underline{\underline{.962''}}\end{aligned}$$

SLAB LENGTH = 125 FEET

POURING TEMPERATURE = 70° F.

$\propto$ = COEFFICIENT OF EXPANSION	L = SLAB LENGTH
ΔT = CHANGE IN TEMPERATURE	ΔL = CHANGE IN LENGTH
W_1 = GROOVE WIDTH AT 70° F.	T_1 = POURING TEMP. 70° F.
W_2 = MAX. GROOVE WIDTH AT -30° F.	T_2 = MIN. TEMP. -30° F.
W = MIN. GROOVE WIDTH AT 120° F.	T_3 = MAX. TEMP. 120° F.

$$\Delta L / 10°F = L \propto \Delta T$$
$$= 1500''(6 \times 10^{-6}) \times 10°F.$$
$$= .09''$$



MAX. JOINT WIDTH = W_2	MIN. JOINT WIDTH = W
$W_2 = W_1 + L \propto \Delta T$	$W = W_1 - L \propto \Delta T$
$= 1.875'' + 1500''(6 \times 10^{-6})(70 + 30)$	$= 1.875'' - 1500''(6 \times 10^{-6})(T_3 - T_1)$
$= 1.875'' + .9''$	$= 1.875'' - .45''$
$= \underline{\underline{2.775''}}$	$= \underline{\underline{1.425''}}$

SLAB LENGTH = 150 FEET

POURING TEMPERATURE = 70°F.

$\propto$ = COEFFICIENT OF EXPANSION

ΔT = CHANGE IN TEMPERATURE

W_1 = GROOVE WIDTH AT 70°F.

W_2 = MAX. GROOVE WIDTH AT -30°F.

W = MIN. GROOVE WIDTH AT 120°F.

L = SLAB LENGTH

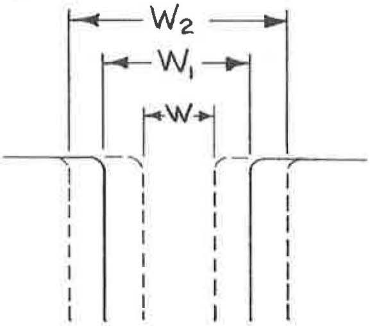
ΔL = CHANGE IN LENGTH

T_1 = POURING TEMP. 70°F.

T_2 = MIN. TEMP. -30°F.

T_3 = MAX. TEMP. 120°F.

$$\begin{aligned}\Delta L/10^\circ F. &= L \propto \Delta T\\ &= 1800'' \times (6\times10^{-6})\,10^\circ F.\\ &= .108''\end{aligned}$$



MAX. JOINT WIDTH = W_2

$$\begin{aligned}W_2 &= W_1 + L \propto \Delta T\\ &= 2.5'' + 1800''(6\times10^{-6})(T_1 - T_2)\\ &= 2.5'' + 1800''(6\times10^{-6})(70+30)\\ &= 2.5'' + 1.08''\\ &= \underline{\underline{3.58''}}\end{aligned}$$

MIN. JOINT WIDTH = W

$$\begin{aligned}W &= W_1 - L \propto \Delta T\\ &= 2.5'' - 1800''(6\times10^{-6})(T_3 - T_1)\\ &= 2.5'' - 1800''(6\times10^{-6})(120+70)\\ &= 2.5'' - .640''\\ &= \underline{\underline{1.860''}}\end{aligned}$$