CRREL REPORT 95-11

CRREL

Sealants and Cold Regions Pavement Seals

A Review

Stephen A. Ketcham

May 1995

Abstract
A pavement joint seal prevents the passage of liquids into the pavement base and the intrusion of solids into the joint. The primary mechanical requirements of a pavement seal are that it respond elastically or viscoelastically to any movement of the joint without failure and that it withstand indentation of hard objects like rocks. Because pavement joint movements and seal deformations can be large, elastomeric sealants are often used to form seals. Winter conditions are recognized as the most critical for a seal because of the possibility that failure stresses will be reached as the joint opens to a maximum and the material stiffens in response to the temperature reduction. This report reviews the specific problems and requirements that cold climates create for the performance of elastomeric seals. Emphasis is placed on the material response behavior that can lead to failure of a seal. In an attempt to clarify the mechanics of sealant and seal performance associated with low-temperature pavement applications and to address the issue of low-temperature stiffening that should be a dominant factor in the selection of a sealant, this report presents background information on the formulation and mechanical properties of elastomeric seal materials and the structural behavior of field-molded joint and crack seals.

For conversion of SI units to non-SI units of measurement consult ASTM Standard E380-93, *Standard Practice for Use of the International System of Units,* published by the American Society for Testing and Materials, 1916 Race St., Philadelphia, Pa. 19103.

CRREL Report 95-11

US Army Corps of Engineers
Cold Regions Research & Engineering Laboratory

Sealants and Cold Regions Pavement Seals

A Review

Stephen A. Ketcham

May 1995

Prepared for
OFFICE OF THE CHIEF OF ENGINEERS

Approved for public release; distribution is unlimited.

PREFACE

This report was prepared by Stephen A. Ketcham, Research Civil Engineer, Civil and Geotechnical Engineering Research Division, Research and Engineering Directorate, U.S. Army Cold Regions Research and Engineering Laboratory. Funding for this research was provided by DA Project 4A762784AT42, *Cold Regions Engineering Technology;* Task CP; Work Unit K01, *Maintenance of Surfaced and Unsurfaced Areas in Cold Regions.* The author thanks Vincent Janoo and Piyush Dutta of CRREL for their technical reviews of this report.

The contents of this report are not to be used for advertising or promotional purposes. Citation of brand names does not constitute an official endorsement or approval of the use of such commercial products.

CONTENTS

ILLUSTRATIONS

Figure

Page

TABLES

Table

Sealants and Cold Regions Pavement Seals
A Review

STEPHEN A. KETCHAM

INTRODUCTION

ASTM standard C 717 defines a seal as a barrier against the passage of liquids, solids or gases and defines a sealant as a material that has the adhesive and cohesive properties to form a seal (ASTM 1991a). For applications to buildings and pavements, a field-molded seal can be formed in a joint or a crack by the curing of a sealant that is applied in liquid, viscous form. The primary mechanical requirements of the seal are that it respond elastically or viscoelastically, over a reasonable design life, to any thermal- or load-induced movement of the joint or crack without adhesive or cohesive failure, and that it cure to a sufficient hardness and remain sufficiently hard so that it will not be damaged by indentation of harder objects. Such a seal is not meant to transfer significant forces of the structure across the joint. On the contrary, for large joint movements, sealants with lower load resistance are most able to deform without failure of the seal or of the structure to which it is bonded.

Joints and cracks in building and pavement structures undergo movements that are dominated in amplitude by the seasonal movements caused by the thermal expansion and contraction of the structural materials. Expansion at higher temperatures and contraction at lower temperatures of the building or pavement materials are realized at the joint as closure during summer and opening during winter, respectively. The result is that a seal in a building or pavement joint must be able to extend during cold periods and compress during warm periods. Cold-period loading of a seal is recognized as the most critical loading period because of the possibility that failure stresses will be reached in the seal or at the adhesive interface as the joint opens and the sealant hardens in response to the temperature reduction. A seal will also be subjected to shorter duration loads that may be critical. For example, joint movements associated with stick–slip motions, daily temperature variations and traffic can induce short duration loads that will be superimposed on existing longer period loads. For each specific application and loading configuration, the cured sealant must have mechanical properties that are appropriate for the structural response and climatic requirements of the seal. In addition, these properties must not degrade significantly when the sealant is exposed to weathering processes, loading cycles, chemical agents and other conditions that are present in its working environment.

In recent years elastomeric sealants have been introduced commercially that are formulated to have relatively low resistance to load at low temperatures compared to conventional and traditional seal materials. The lower resistance at lower temperatures is a result of a more flexible material formulation and of a lower temperature of the material's transition to harder behavior. This report is concerned with the behavior of these elastomeric sealants, which are often simply called "low modulus sealants," for sealing joints and cracks in asphalt and portland cement concrete pavements in cold regions and with the specific problems and requirements that cold climates create for seal performance. Emphasis is placed on the material response behavior that can lead to failure of a seal, rather than on strength of sealants and failure of seals. Several low modulus elastomeric compounds have been marketed as pavement sealants. A significant concern for pavement seal designers should be the transition temperatures below which these sealants in pavement seal configurations perform inadequately because of the stiffening of the material. In an attempt to clarify the mechanics of sealant and seal performance associated with low temperature pavement applications, and to address the issue of low temperature hardening that should be a dominant factor in the selection of a sealant, this report presents background information on the formulation and mechanical properties of elastomeric seal materials and the structural behavior of field-molded joint and crack seals.

ELASTOMERS AND SEALANT FORMULATIONS

Commercially available sealants are produced from a variety of materials. Because the ideal behavior of a pavement joint seal is that of an elastomer, it is revealing to describe sealant formulations in the context of elastomers and elastomeric compounds.

"Elastomer" is a term often used for rubber and polymers that have properties similar to those of rubber (e.g., ASTM 1991b). Elastomers are polymers with a particular type of molecular structure. Specifically they are linear, amorphous (i.e., noncrystalline), high molecular weight polymers in which the chains of the molecular structure are flexible and cross-linked (e.g., Hearle 1982). The flexibility and cross-linking of the polymer chains allow elastomers to behave elastically, as the name implies, such that they are capable of recovering from large deformations. Mark (1982) has listed three molecular requirements for a material to exhibit this rubber-like elastic behavior:

- The material must consist of polymeric chains.
- The chains must have a high degree of flexibility.
- The chains must be joined into a network structure.

In this context the terms elastomer and rubber are used as synonyms, and the broad range of natural and synthetic rubbers and rubber compounds that behave like elastomers can be studied in a single context because the behavior can be attributed to this molecular structure. It is of interest to note that when the molecular chains lose their flexibility in response to a temperature reduction, there is a transition in the material behavior of the polymer from a elastomeric behavior to that of a hard material, e.g., glass. The transition is referred to as the "glass transition."

Elastomeric compounds are marketed commercially as formulations that consist of the base elastomer or elastomers together with additives. Various formulations with the same base elastomer can be developed for very different applications. For example, polyurethane formulations can be used in elastomeric applications ranging from shoe soles to joint sealants. Although elastomeric formulations can be designed or advanced by theoretical modeling techniques, the development of most is primarily empirical.

Additives are used primarily to improve specific properties of a formulation. A "plasticizer" is an additive that increases the flexibility of a compound. More specifically a plasticizer reduces the stiffness of the base elastomer at a given temperature, lowers the temperature for which elastomeric behavior can occur, increases the strain at which failure occurs in the elastomer, and increases its impact strength at lower temperatures (Immergut and Mark 1965). In some sealant formulations, plasticizers are used in this way, i.e., to lower the modulus of the cured material and to improve its low temperature capabilities. "Filler" refers to material that is used primarily to add bulk to the base elastomer, although the term is often used to designate any additive other than plasticizers that has an impact on the properties of the compound. At times fillers have been used to improve the profit margin of the manufacturer at the expense of the desired elastic material properties. Panek and Cook (1984) have suggested that such economic-based compounding has been the cause of the inadequate performance of some asphalt rubber highway joint seals in the past. Other additives that might be used include coloring agents, curing ingredients, adhesive agents, and ultraviolet light and oxygen stabilizers. Usually exact formulations of elastomeric compounds are kept as trade secrets of the manufacturer. Table 1 includes several nonspecific sealant formulations that have been published by Panek and Cook (1984).

Elastomers are used as the base polymer of commercially available sealants so that seals formed by these sealants will respond elastically to service loads and deformations. The base polymers of sealants include natural rubber, styrene-butadiene rubber, neoprene, silicone, polyurethane, polysulfide and polyvinyl chloride (Panek and Cook 1984). The sealant formulations range from asphalt and rubber compounds to coal tar and polyvinyl chloride compounds to silicone sealants. Often categorical distinctions are made in the applications literature between asphalt rubber sealants, coal tar rubber sealants and other polymeric sealants. In the context of elastomeric compounds, however,

Table 1. Example sealant formulations, percentages by weight. (After Panek and Cook 1984.)

Urethane sealant: urethane polymer, 35–45%; fillers, 30–40%; colorants, 2–3%; thixotropic agents, 1–2%; adhesion additives, 1–3%; plasticizers, 15–25%; solvent, 0–4%

Silicone sealant, structural grade: silicone polymer, 65–75%; silicone oil plasticizer, 5–15%; silica filler, 15–25%; curing agent, 3–5%; adhesive additive, 1–3% (lower modulus silicone sealants would have a higher amount of silicone oil plasticizer and less cross-linking trifunctional silane complex)

Polysulfide sealant: polysulfide polymer, 30–40%; various fillers, 30–40%; plasticizers, 20–25%; curing agents, 2–5%; adhesion additives, 1–3%; miscellaneous, 1–3%; solvent, 3–5%

Hot-poured rubber asphalt sealant: ground rubber (e.g., styrene-butadiene rubber ground to a 30-mesh size), at least 25%; asphalt, remainder

Hot-poured polyvinyl chloride (PVC) and coal tar: PVC powder dispersed in a coal tar base

in which additives are blended and reacted with the base elastomer(s) and cured to form the final product, the asphalt and coal tar in such products can be categorically regarded as fillers or plasticizers and adhesive agents, and the chemical and physical reactions between these materials and the rubber polymer can be viewed as a typical curing process that yields an elastomeric material. Indeed, it would be advantageous to consider all elastomeric-based sealants, including asphalt and coal tar rubbers, in a single context with respect to formulation, so that engineers who select and use these materials will have a mechanical framework that can be utilized to compare and contrast them.

Different elastomers and elastomeric formulations can attain their application configuration, cross-linking and mechanical properties through a variety of curing reactions and mechanisms. Sealants can be formulated to cure by chemical and physical reactions and solvent release. The reactions can be triggered, for example, by heat, as in the case of the hot-poured sealants, or by catalysts, as in the case of moisture-induced cure of silicone sealants.

MECHANICAL BEHAVIOR OF SEALANTS

In general, the commercially available, low modulus sealants that are used for sealing joints and cracks in pavements are formulated to behave with rubber-like characteristics. That is, these materials are formulated so that a seal made from a low modulus sealant, loaded to a relatively large deformation, will return to its original shape and size upon unloading. For a description of the mechanical properties of sealants it is helpful to consider sealant behavior in the context of the behavior of rubbers and elastomers since the material response features of practical interest for sealing joints and cracks are clearly revealed, and since the elastomeric qualities that a seal displays when subjected to field loadings and conditions can be used to judge the effectiveness of the sealant. In addition, if a seal formed by an elastomeric-based sealant does not behave elastically, e.g., if the seal deforms plastically or if it behaves with excessive viscous behavior, the deviation from ideal elastomeric behavior could be quantified and an assessment of the sealant could be made. This section describes the mechanical behavior of rubber-like materials and low modulus sealants from a phenomenological perspective. The section also describes the hyperelastic material model, which is conventionally used as a constitutive model for elastomeric materials, and its potential application to sealants.

Phenomenological behavior of rubbers and elastomers

In unconfined loading configurations the deformations of a rubber structure will generally be dominated by shear distortions. This is because the volume compressibility of elastomers and elastomeric formulations of rubber-like materials is, relative to the shear deformability, very low. Typically a rubber will have a bulk modulus that is orders of magnitude greater than its shear modulus. As a result, the material is constrained geometrically by its own response to deform primarily by distortions. This is particularly true for the base elastomer, and, depending upon the additives, is likely to be the case for an elastomeric formulation.

The shear deformability of rubbers has been investigated using different loading and test speci-

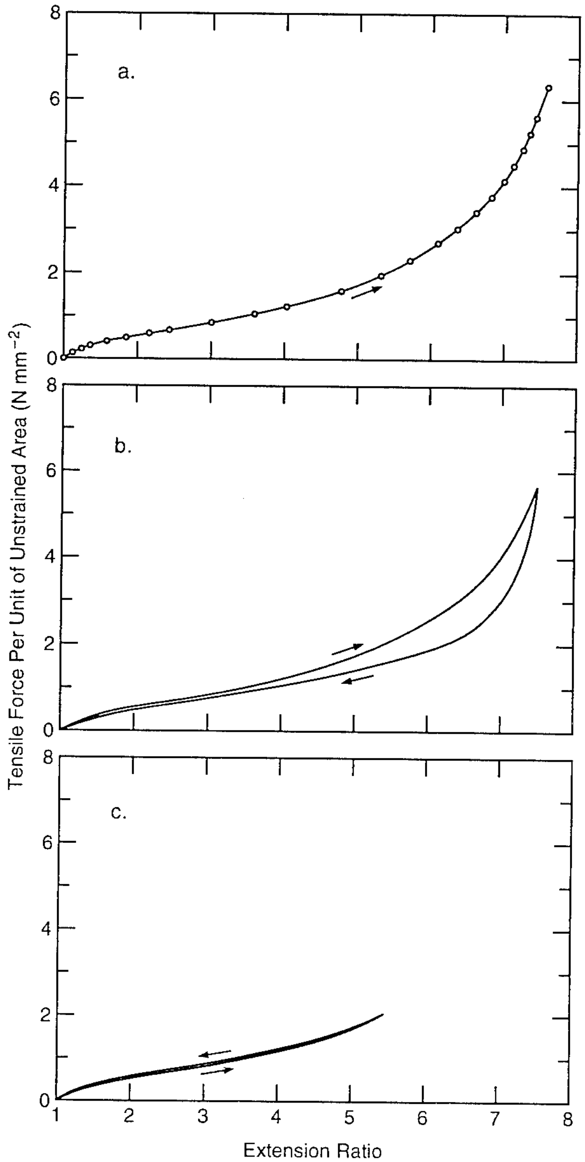


Figure 1. Results from three simple tension tests of vulcanized natural rubber. (After Treloar 1975.)

men configurations. Traditionally, for obtaining material stress-strain data under homogeneous stress and deformation conditions, load and deformation responses have been measured in simple tension, equibiaxial tension and pure shear tests. Torsion tests, which inherently generate inhomogeneous stress and deformation conditions, can provide material stress–strain data as well (Penn and Kearsley 1976), by using a technique for calculating material stress–strain data from the measured torque and axial force of the torsion sample (Kearsley and Zapas 1980). For standard comparative measures of material properties the simple tension configuration is often used (e.g., ASTM 1991d).

Test programs that incorporate these experimental configurations are sometimes devised to investigate material behavior, to calibrate phenomenological constitutive models of rubber elasticity behavior that can be used for material and structural response calculations, and to verify predictions made using the constitutive models.

Simple tension tests of elastomers yield response curves like those shown in Figure 1. The figure relates force per unit of unstrained area to extension ratio, which is defined as the deformed specimen length normalized by the undeformed specimen length. The data in the figure are for a vulcanized natural rubber tested at room temperature, and are published by Treloar (1975).

Figure 1 includes the force-extension ratio responses measured in three simple tension tests. Curve (a) illustrates the response of a specimen that was loaded to failure, whereas curves (b) and (c) illustrate the responses of specimens that were loaded and unloaded without failure. Based on the curves (b) and (c) Treloar (1975) noted that up to an extension ratio of about 5.5 the material response was substantially reversible, but that loading to a higher extension resulted in significant hysteresis. Curve (c) illustrates clearly the low resistance, high extension, nonlinear elastic response that is the characteristic feature of the behavior of rubber materials. For example, it is roughly the behavior of the material of a rubber band when stretched.

Implicit in this description of an elastomer is a temperature range for which rubber-like behavior occurs. The transition from rubbery to glassy behavior (the glass transition) is often characterized by a single temperature, although, unlike a crystalline material, the mechanical behavior changes gradually over a temperature range. The transition occurs because the chains of the amorphous molecular network become less flexible with decreasing temperature until the structure is rigid. Figure 2 illustrates the changes in the load and extension response that are typically observed in polymers that are tested in simple tension tests at different temperatures. Only above the temperature range of the glass transition will a polymer in simple tension tests deform with homogeneous strains and behave like an elastomer (Ward 1983). Within and below the transition range the deformation will not be homogeneous, and ductile or brittle failure can occur. The figure illustrates that a material intended for use as an elastomer will actually behave as a stiff and perhaps brittle material when its temperature is below the glass transition temperature.

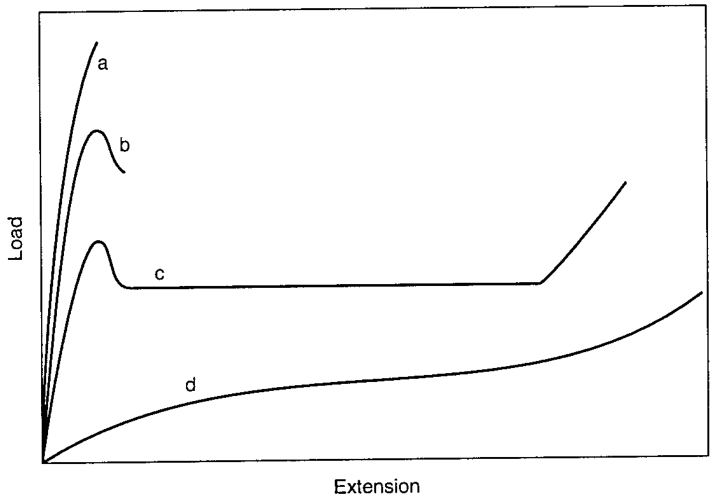


Figure 2. Schematic depiction of load and extension responses of a typical polymer tested in simple tension tests at different temperatures, from temperature well below the glass transition temperature, i.e., curve a, *to temperature above the glass transition temperature, i.e., curve* d. *(a) brittle fracture, (b) ductile failure, (c) cold-drawing, and (d) rubber-like behavior. (After Ward 1983.)*

The glass transition temperature is often quantified by the measurement of the load and deformation response of a material specimen during low strain amplitude harmonic loading experiments, creep tests and stress-relaxation tests. From the dynamic measurements of harmonic loading tests, elastic moduli of the material can be calculated for the material's response at various frequencies and temperatures. Because the responses of polymers can have a viscous component, the moduli that are calculated are complex quantities. Figure 3 depicts the real part of the complex Young's modulus plotted against the temperature of the material and the frequency of the harmonic loading for the synthetic rubber Buna N. The data were originally published by Nolle (1950). This figure illustrates that the glass transition occurs primarily between 0 and –20°C for lower frequency loading, but that the transition occurs at higher temperatures for higher frequency loading. These features, i.e., that glass-like behavior can occur both at low temperatures and at high frequency loading rates, are typical of elastomers.

The distinction between rubbery and glassy behavior is made here to clearly illustrate the impact that temperature can have on the behavior of sealants. A distinction between rubbery and viscous behavior should be made as well, however, since the effects of the viscous response of predominantly rubber-like materials can be more than subtle, and since compounding of elastomers with additives can yield overly viscous formulations that behave with excessive creep and stress relaxation for sealant applications. ASTM (1991b) provides a definition for rubbery behavior by suggesting that a specimen made from rubber, when stretched to twice its length for a duration of one minute, will return upon release to 1.5 times its original length within one minute. This definition implies that a distinction can be made between predominantly rubbery and viscoelastic behaviors, while recognizing that rubber behavior incorporates some viscoelasticity.

Failure of elastomers is typified by brittle fracture that occurs only after large, nonlinear elastic deformations, with any plastic deformation being restricted to a very small volume of the material around the fracture (Williams 1984). Bueche and Berry (1959), however, have suggested that, for predictions of tensile failure, a critical stress criterion rather than a fracture mechanics-based criterion is preferable. For simple tension specimen configurations, Smith and Stedry (1960) have made measurements that demonstrate the influence that strain rate and temperature have on tensile failure, and have shown that a tensile failure envelope connecting rupture points of the stress–strain

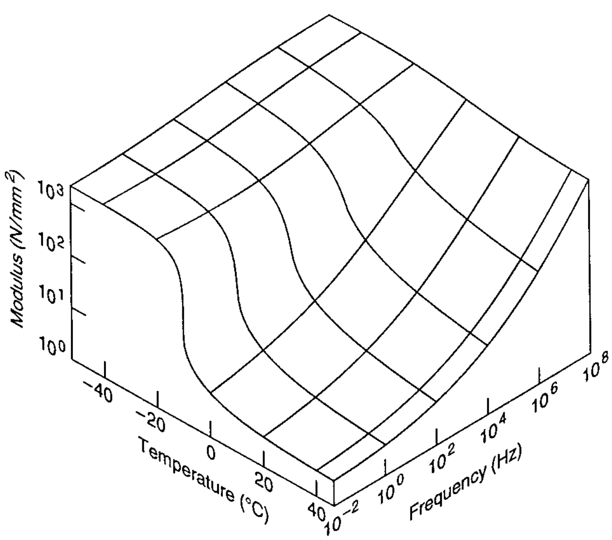


Figure 3. Real part of the complex Young's modulus plotted against the temperature of the material and the frequency of the harmonic loading in a three-axis plot for the synthetic rubber Buna N. (After Hearle 1982 and Nolle 1950.)

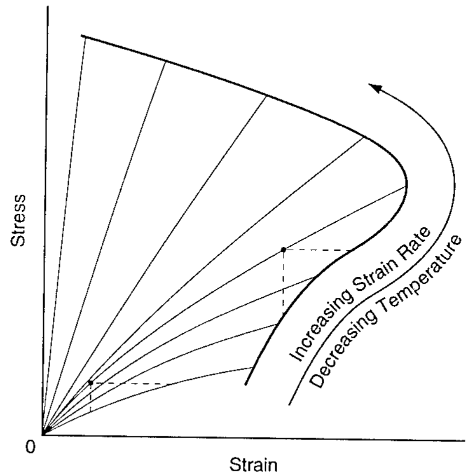


Figure 4. Variation of the simple tension stress–strain curves of an elastomer with strain rate and temperature, and an envelope of failure points. (After Ward 1983 and Smith and Stedry 1960.)

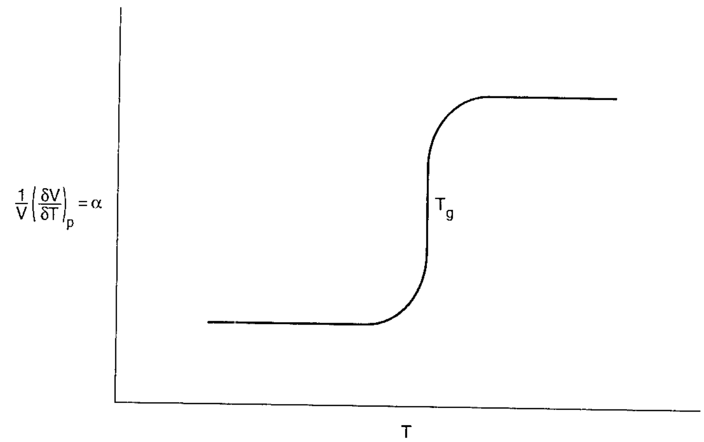


Figure 5. Schematic illustration of the variation of the coefficient of volume expansion α with temperature T for polymers, and the glass transition temperature T_g. (After Eisenberg 1984.)

data can be formed that reflects this influence. Figure 4 shows a schematic illustration of their data.

Brittle fracture of an elastomer after large deformations should be distinguished from brittle fracture of the same material in a glassy state. The use of the "brittle fracture" to describe rubber failure can be misleading and is not often used. In addition, the transition from rubber-like behavior to glassy behavior should be distinguished from a ductile to brittle transition. The terms ductile and brittle describe primarily the failure response at large strains, whereas the terms rubbery and glassy encompass mechanical response behavior of a greater extent.

Although elastomers generally behave as incompressible materials in a mechanical loading context, thermally induced volumetric strains can be significant and, if constrained, can have a significant influence on the stresses in the material. The thermal coefficient of volume expansion of a polymer is another property that varies with temperature such that the glass transition temperature is revealed. Figure 5 illustrates this variation schematically.

Volume changes in rubbers can also be caused by exposure to organic liquids such as hydrocarbons (Treloar 1975). Rubber materials can swell and contract with the exposure and expulsion of the liquids, and the volume compressibility can increase with exposure such that an assumption that the rubber is incompressible is no longer valid (Treloar 1975). Swelling does not imply that any chemical interaction between the rubber and the liquid has occurred, however. For rubbers the process is simply a physical mixing process in which the molecules of the liquid diffuse into the molecular structure of the rubber (Treloar 1975). Volume changes due to shrinkage during curing of the rubber formulation can be significant, particularly if the curing process includes evaporation of solvents (Panek and Cook 1984). As mentioned above, if the volumetric strains are constrained, the material stresses will be affected.

Hyperelastic constitutive model

To characterize the stress–strain response of an elastic body undergoing large deformations, it is sufficient to specify the form of the strain energy function W as a function of the deformation or current strain (e.g., Rivlin 1956, Green and Adkins 1960). The derivative of the strain energy function with respect to a strain component gives the corresponding stress component. The term hyperelastic has been used to describe such an ideal elastic material (Malvern 1969).

The form of strain energy functions of rubbers has been deduced from both molecular considerations and phenomenological experiments, and similarities between the forms have been found (Treloar 1975, Green and Adkins 1960). Based on experimental measurements, Rivlin and Saunders (1951) have suggested that, for vulcanized natural rubber,

$$W = C(I_1 - 3) + f(I_2 - 3), \qquad (1)$$

where I_1 and I_2 are strain invariants for an isotropic, incompressible material, C is a constant, and f denotes "a function of." Specifically, $I_1 = \lambda_1^2 + \lambda_2^2 + \lambda_3^2$ and $I_2 = 1/\lambda_1^2 + 1/\lambda_2^2 + 1/\lambda_3^2$, where the λs are the extension ratios, i.e., ratios of the current length to the original length, in the principal directions. The first term of eq 1 has been found by relating the change in molecular dimensions to macroscopic strain measurements from homogeneous strain-loading experiments, and the last term has been called a "correction" term (Treloar 1974). A large body of work has been conducted to establish improved or alternative forms of the strain energy function for isotropic rubber materials from a phenomenological perspective (see Treloar 1975, for a review). For example, the following polynomial form of the strain energy density function (e.g., Rivlin and Saunders 1951) is often used for phenomenological modeling:

$$W = \sum_{i=0,j=0}^{\infty} C_{ij}(I_1 - 3)^i (I_2 - 3)^j, \quad C_{00} = 0. \qquad (2)$$

The experimental determination of the strain energy function is typically a detailed task. Rivlin and Saunders (1951) described a technique using biaxial loading experiments of rubber sheets that has been adapted by many workers. In this technique $\partial W/\partial I_1$ and $\partial W/\partial I_2$ are calculated from measurements as functions of I_1 and I_2, and the functions are used to define eq 1. The conditions during the experiments dictate the thermodynamic nature of the strain energy function that is found, e.g., that the strain energy function is the function for isothermal and constant pressure conditions (Ward 1983). Other techniques have been developed as well. For example, Penn and Kearsley (1976) describe a data reduction technique for torsion experiments that allows $\partial W/\partial I_1$ and $\partial W/\partial I_2$ to be calculated from torque and normal force measurements at different torsion angles.

Implementations of strain energy functions for large deformation response predictions of rubber structures are described for several homogeneous and inhomogeneous deformation problems by Rivlin (1956). Numerical implementations of hyperelastic models, using the finite element method with large deformation capabilities, are described, for example, by Hibbitt et al. (1989) and Finney and Kumar (1988). The effect of temperature on the structural response can be incorporated in the analysis by measuring the strain energy as a function of temperature as well as strain.

Because a response predicted by a hyperelastic model is independent of the previous state of strain, the predicted stresses are independent of the strain history and deformation rate, and the response is that of a conservative system. As such, hyperelasticity cannot model viscous or plastic behavior, such as hysteresis, creep, stress relaxation and permanent deformation (Green and Adkins 1960). However, for rubber-like time-dependent materials, McKenna and Zapas (1986), citing Rivlin (1956), describe the validity of using isochronal stress–strain data from stress–relaxation tests, measured at relatively short times after a rapid strain application, as an estimate of the equilibrium data for calculating strain energy functions for use in finite elasticity calculations. Thus, if the data of the time-dependent material response are treated correctly, the time dependence can be ignored for purposes of the finite deformation calculations, and the results could be viewed as the response at a given time, e.g., the long-term response.

Examples of sealant behavior

Previous experimental studies of the mechanical behavior of joint and crack sealants have relied primarily on structural configuration tests rather than material property tests to obtain measures of the sealant response. Although structural configuration tests can reveal "apparent" system properties (Gent and Lindley 1959), material properties cannot readily be found from these tests. Results from structural configuration tests will be reviewed in the following section.

Catsiff et al. (1970a) have described material test data from several sealant materials, including polysulfide, silicone and asphalt-polyurethane sealants. They presented measurements indicating that an incompressibility assumption is valid for analyzing structures formed from these materials, and emphasized the validity of the incompressibility assumption for the sealant formulations, not just the base-elastomer. They further suggested that stress and elongation data in an isochronous form, e.g., stress and extension data for a given time after the loads are applied in stress-relaxation tests, are appropriate for structural analysis techniques in which time-dependent behavior is not incorporated. This suggestion is consistent with the method suggested by McKenna and Zapas (1986) for calculating the strain energy function for quasi-elastomeric materials, as mentioned above. Catsiff et al. (1970a) presented data illustrating the validity of this technique for sealants.

Tensile failure and extension data from simple tension tests of various silicone joint sealants have been described in the literature by Spells (1987) and are reproduced in Table 2. The sealants were designated by Spells as high modulus, medium modulus, and low modulus sealants in order to demonstrate their range of deformation capabilities, and were tested according to standard procedures (ASTM 1991d) at near room temperature. For each category the table lists the force per unit of the original, unstrained area at an extension ratio of 1.5, and the extension ratio at breaking failure.

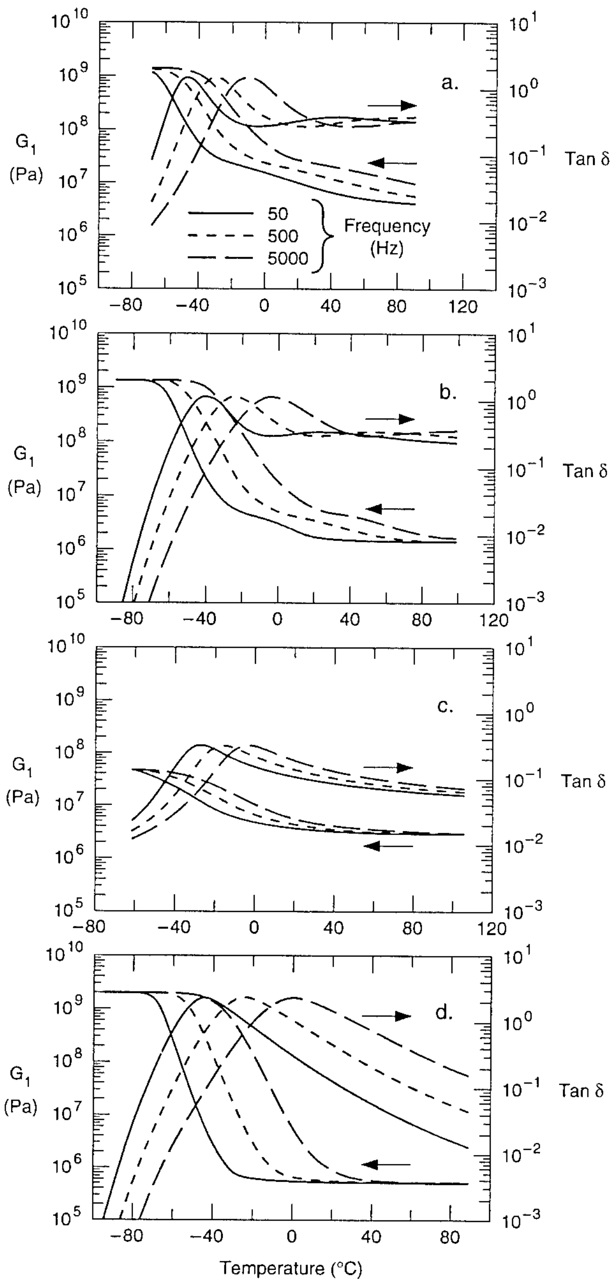


Figure 6. Examples of the real part of the complex shear modulus G ($G = G_1 + iG_2$) and the loss factor tan δ ($\tan \delta = G_2/G_1$) as functions of temperature from low-strain harmonic loading tests of (a) a polysulfide sealant, (b) a polysulfide elastomer, (c) a urethane elastomer, and (d) a natural rubber, all tested at three loading frequencies in beam tests. (After Nashif and Lewis 1991.)

Table 2. Tensile failure and extension data from simple tension tests of various silicone joint sealants. (From Spells 1987.)

Sealant classification	*Force per unit unstrained area at extension ratio = 1.5 (kPa)*	*Extension ratio at breaking failure*
High modulus	690	5
Medium modulus	276–690	5–12
Low modulus	276	12

Very few data exist in the literature regarding the effect that temperature has on sealant properties, although in the rubber and polymer industry such material property data are routinely generated for evaluating the effectiveness of the material, and standard test methods are suggested for obtaining the data (e.g., ASTM 1991c). One example of shear modulus vs. temperature data from low-strain harmonic loading tests of a sealant is shown in Figure 6. The data are for a polysulfide sealant tested at three loading frequencies using a beam test, from a publication of Nashif and Lewis (1991). The real part of the shear modulus G($G = G_1 + iG_2$) and the loss factor tan δ ($\tan \delta = G_1/G_2$) are shown. Also shown from this publication, for purposes of comparison, are corresponding data sets for a polysulfide elastomer, a urethane elastomer and a natural rubber.

More general reviews of the characteristics of sealants have been given by Panek and Cook (1984) and the American Concrete Institute (ACI 1993).

MECHANICAL RESPONSE OF SEALS

The current state of knowledge of the mechanical response of joint and crack seals comes primarily from field and laboratory experimental studies of the deformation capabilities of pavement and building seals. As indicated by the extent of the experimental work that is documented in the literature and by the concerns of the practitioners who are charged with sealing joints and cracks, the structural performance of seals is of great interest to civil and pavement engineers. Although it is generally recognized that the low-temperature extreme of the seasonal temperature cycle can lead to failure of the seal if the material hardens significantly and the seal is extended by the movement of the joint or crack (e.g., ACI 1993, Beech 1985, Catsiff et al. 1970a), very little work has been conducted to quantify the effect of low-temperature variations on the structural response of seals. In this section the basic geometry of seal structures and their loading is discussed; conventional experimental techniques for studying pavement joint and crack seals are described; and the mechanical response of seal structures to joint movements, as revealed by a selection of analysis results and experimental measurements, is reviewed.

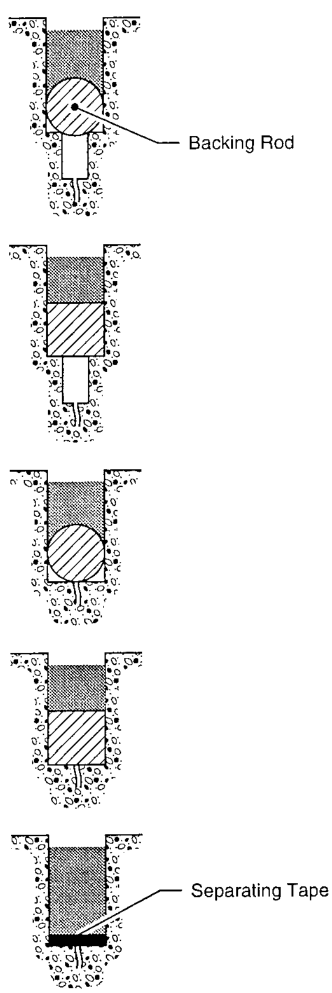


Figure 7. Butt joint seal cross sections in joint and crack locations with different practical variations of joint preparation, uses of auxiliary materials and seal geometries.

Basic structural geometry and loading configurations of seals

In general, portland cement concrete pavements are constructed with regular joint patterns and spacing to avoid cracking of the pavement from thermal response and shrinkage of the concrete, whereas asphalt concrete pavements are rarely constructed with built-in joints. When cracks are sealed in asphalt concrete pavements, where crack patterns can vary from regular spacings of relatively straight transverse and longitudinal cracks to irregular patterns of meandering cracks, it is conventionally recommended that butt joint reservoirs be formed along the cracks using sawing or routing construction techniques (e.g., Lynch 1990). Some authors, however, without presenting analyses to support their contentions, have suggested that seal performance is not improved by this technique (Panek and Cook 1984). Further, in the case of reflection cracks in asphalt concrete overlays of portland cement concrete pavements, where the crack patterns typically follow the regular joint pattern of the portland cement concrete pavement, it is also conventional practice to construct butt joint reservoirs along the cracks by sawing or routing the cracks. For these reasons little distinction is made in this section between seals formed at joints and at cracks and between seals in portland cement concrete joints and in asphalt concrete joints, although the term crack is used in reference to asphalt concrete pavements.

In an engineering design context, a pavement joint or crack seal formed from a sealant can be described as a long structure with a butt joint cross section such as one of those depicted in Figure 7. This figure shows typical seal cross sections in joint and crack locations with variations of joint preparation, uses of backing rod and separating tape, and seal geometries. Often in practice the constructed cross sections will deviate from the ideal configurations illustrated due to construction irregularities, backing rod installation or irregularities in the crack or joint. For crack seals in particular, it is also likely that there will be variations along the length of the seal as a result of the meander of the fracture in the pavement surface, and it may be that a joint reservoir is not prepared during the sealing operation and the seal is formed in the cavity of the crack. Although not quantified by realistic structural analyses of seals, it is generally recognized that when there is significant deviation from the butt joint configuration, there can be premature failure of a seal because the load distribution results in increased stresses in the seal (e.g., ACI 1993, ASTM 1991f).

A pavement seal can be subjected to many types of loadings. These include loadings caused by seasonal, daily and traffic-induced movements of the joint or crack opening; the direct loading of the seal itself by tires or hard objects such as small rocks under the weight of tires; the forces of constraint caused by the volume change response of the seal material that results from the curing process, temperature variations or the interaction of the seal material with a foreign substance such as jet fuel; and the forces of constraint caused by changes in the stress–strain behavior of the seal material induced by temperature variations or the aging of the material. The distribution of loads on pavement joint seals as a result of long- and short-duration movements of the joints is not a directly measurable quantity, whereas joint movements can be measured directly. As a consequence the "movement capability" (see e.g., Panek and Cook 1984, ASTM 1991f) of a model seal in terms of either a safe-working elongation or an ultimate, failure elongation, rather than a load capability in terms of the sealant's strength, is commonly used to comparatively describe sealants. Examples of horizontal joint movement measurements are the data of Minkarah et al. (1982), which are from portland cement concrete highway test sections in Ohio with regular joint spacings. Minkarah et al. mentioned that short-term measurements of ±25% were typical for joints formed by 6.4- and 12.2-m highway sections, and were greater than longer cyclic movements. Such movements can be roughly estimated with manageable structural analysis calculations. For example, the American Concrete Institute (ACI 1993) has suggested an analysis technique for predicting horizontal movements of joints in portland cement concrete pavements due to thermal contraction and expansion of the concrete material.

Conventional performance testing for studying the load and deformation response of joint and crack seals

As mentioned above, it is typically a "movement capability" of a model seal, in terms of either a safe or ultimate extension, compression or other deformation, that is used to summarize the load and deformation performance of the corresponding sealant product. In general, although an apparent modulus is often reported for a model seal, conventional experimental techniques for characterizing a seal's response to load sometimes adopt the movement capability concept without concern of the load. These techniques are intended to provide performance data so that a seal designer can ensure that the working movement capability of a seal is greater than the movement that the joint will experience.

Tests of model seals are generally conducted using block-shaped seal specimens constrained between parallel surfaces of a given substrate. Performance-based standard tests of these model seals (Beech 1985), for both the pavement and building seal industries, have been developed primarily to provide a basis for quantifying and indexing movement capability in the context of the movements associated with seasonal joint opening and closing. As suggested by the standards, these tests are typically conducted at a specific low temperature in recognition of the severity of the low temperature extreme. None of the standard methods incorporate test series for measuring the possible stiffening of the response as the temperature is lowered, however. Many other laboratory and field tests that are not standard have been performed to measure the movement capability of model seals. These include laboratory tests of a model seal's response to transverse movements (e.g., Shisler and Klosowski 1990), and long-duration field tests using thermally designed loading fixtures that allow a model seal to be subjected to environmental weathering and temperature variation-induced joint movements (e.g., Karpati et al. 1977). Regarding the latter, although an extensive amount of research on sealant movement capability has been performed using outdoor strain cycling exposure racks (e.g., Karpati 1980, 1989), continuous load and deformation measurements with strain cycling have not been made, and thus quantitative structural response information has not been obtained during the exposure. Such measurements could provide significant quantitative data regarding temperature-induced hardening and its effect upon the load and deformation response of seal specimens. However, typically only the joint movement and temperature have been measured while the seals are on the rack, and changes of the model seals have been noted visually (Karpati 1980).

Beech (1985) has suggested that tests of model seals yield superior results for measuring movement capability, compared to tests of actual seals in field service, because the results from in-service tests reflect a specific set of circumstances and do not lend themselves to statistical analysis. Indeed, when the goal of the test is to determine a capability of a sealant to form a seal, independent of the workmanship and other conditions peculiar to a given application of the sealant, such an isolation of variables is required to improve the degree of control of the experiment. Beech stated that the long-duration exposure and seasonal cycling tests noted above (Karpati et al. 1977) are the "closest practicable approach" to in-service tests.

There is confusion in the sealant literature regarding the nature of tests on model seals, however. In particular, although the block-shaped seal specimens do not respond with a true plane-strain response because of their typically short length, the models are often assumed to represent long joint seal structures. Additionally, research test results of the model structure are often reported as if a homogeneous material response rather than an inhomogeneous structural response has been measured. For example, when model seals are tested in material testing apparatuses, the nominal stress and strain are often used to calculate the apparent modulus exhibited by the structure, yet the value is typically reported simply as a "modulus" as if the structural response could be considered as homogeneous. Indeed, a leading textbook for sealants (Panek and Cook 1984) has incorrectly suggested that the modulus of elasticity of the sealant can be calculated from experiments on bonded model seals with 1.3- × 1.3-cm cross sections, without alerting the reader that the result is the apparent modulus of the structural system rather than the material modulus. Furthermore, "creep" and "stress-relaxation" tests have been conducted using model seal specimens, without following the conventional approach of using a structural solution to calculate the corresponding material response (Cook 1965a, Sandberg and Rintala 1990), even though creep and stress-relaxation refer to material responses and not system responses. The implication is that, in general, researchers in this field do not distinguish between the response of the material and the response of the structure formed from the material. Evidently this lack of distinction has led to a conventional practice in which butt joint seal structures are tested not only to ascertain the behavior of a particular structure, but also to specify the behavior of the sealant material, and to do so without suggesting that the behavior is the apparent material behavior for the particular structure. For the practicing engineer this distinction may not be of concern, but it is important that the researchers who establish design criteria do so with a firm understanding and clear communication of such basic mechanics.

Regarding the performance testing of model seal structures as the conventional technique for specifying the behavior of the corresponding sealant material, Catsiff et al. (1970a) state

> Relevance of the measurements obtained to actual use is likely to require an almost intuitive appreciation of past experience. Special-purpose tests may be devised, but the multiplicity of end-use requirements can be expected to yield an equal multiplicity of such tests. In any case, correlation of field failures or successes with numerous laboratory tests and controlled field tests is bound to be a tedious and time consuming operation.

Their remarks underscore the need for more engineering mechanics-based specifications of sealant behavior, such that practical decisions can be made competently by an engineer who does not have years of experience with special-purpose performance tests.

In addition to movement capability experiments, other load and deformation response tests are incorporated in standard test methods to mimic the load associated with indentation of hard objects. For example, in ASTM D 3407 (1991e), which is a standard for testing joint sealants for concrete and asphalt pavements, these tests are penetration index tests of cured sealant specimens.

Response of seals to joint movements: Results from analyses and experiments

In the field of building and pavement sealants, the most widely used and referenced technique for the analysis of the response of seals to joint movements is the nominal strain calculation approach of Tons (1959). Tons used observations of elastomer-based seals to suggest that the deformed top and bottom surfaces of a long butt joint seal are constrained to have a parabolic shape, and to assume that the material of the seal is incompressible. His analysis consisted of calculating an apparent, nominal strain along "the parabolic curve-in line" so that the movement capability of seals with different shape factors could be compared. He used his observations, constraint assumptions and calculations to suggest guidelines for shape factor design, stating that "for like conditions, the greater the width of the joint, the less the sealer will be strained for the same percentage of joint opening," and that "the shallower the joint is sealed, the less the sealer will be strained when the joint opens, other conditions being the same." Tons observed that at large deformations the de-

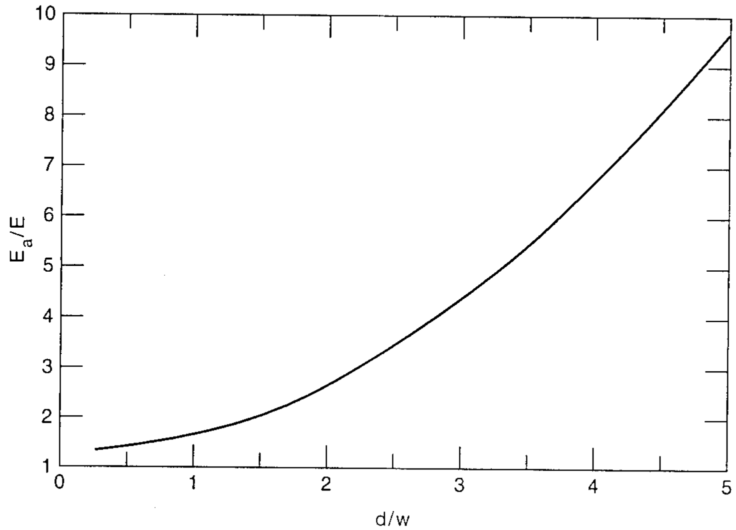


Figure 8. Ratio of apparent Young's modulus to Young's modulus of the material, E_a/E, *of a rubber block in the configuration of a long butt joint seal, in relation to the shape factor* d/w. *(From Gent and Lindley 1959.)*

formation pattern deviated from the parabolic shape and the nominal strain distribution along the parabolic surface varied slightly from a "uniform" nominal strain. The calculation of a nominal strain that Tons suggested, and the use of the calculations to compare the movement capability of seals formed with different shape factors, is an approach that has been incorporated into design manuals (ACI 1993) and used extensively by practicing engineers.

Another publication from 1959 describes a simple analytical solution for shape factor design that is based on structural mechanics theory. Gent and Lindley (1959) presented results of elasticity analyses and experiments designed to assess the effect of a shape factor on the apparent modulus of rubber blocks, i.e., the stiffness of the blocks, in butt joint seal configurations under compression loads. They showed that the apparent Young's modulus E_a of a rubber block in the configuration of a long butt joint seal, in relation to the Young's modulus of the material E, the width of the joint w and the depth of the seal d, can be approximated by

$$\frac{E_a}{E} = \frac{4}{3} + \frac{1}{3}\left(\frac{d}{w}\right)^2 . \tag{3}$$

The relation is illustrated in Figure 8. It was derived for volume-incompressible rubbers at small deformations, and was shown to compare well to the experimental behavior of compressed rubber blocks. Applying the relation to joint seals, for ratios of d/w less than 1, the apparent modulus of a seal can approach a value that is 4/3 the sealant modulus, yet the apparent modulus can increase dramatically with increasing d/w ratios. This information could be used in the design choice of d/w to ensure that stresses in the seal and at the adhesive interface will not be excessive, i.e., to ensure that a seal formed from a low modulus sealant will not respond with a high stiffness. The relation provides a clear structural rational for the need to maintain control over shape factors in crack-sealing jobs through such means as rout and seal or saw and seal techniques. Gent and Mienecke (1970) presented similar solutions for bending and apparent shear joint movements, which could also be used for joint seal shape design. Gent and Lindley (1959) further showed that the eq 3 relation might not apply directly to volume-compressible rubber formulations, although they suggested that the relation could be modified to predict the response of such compounds. Chalhoub and Kelly (1991) presented an instructive derivation of the eq 3 relationship, and also considered volume compressibility.

For an approximate analysis of the larger deformation compression or extension responses of the rubber in a butt joint seal configuration, Gent and Lindley (1959) utilized an elasticity-based solution (Treloar 1975) of the stress–strain response of a rubber in pure homogeneous compression or extension, with the Young's modulus replaced with the apparent Young's modulus. From the solution

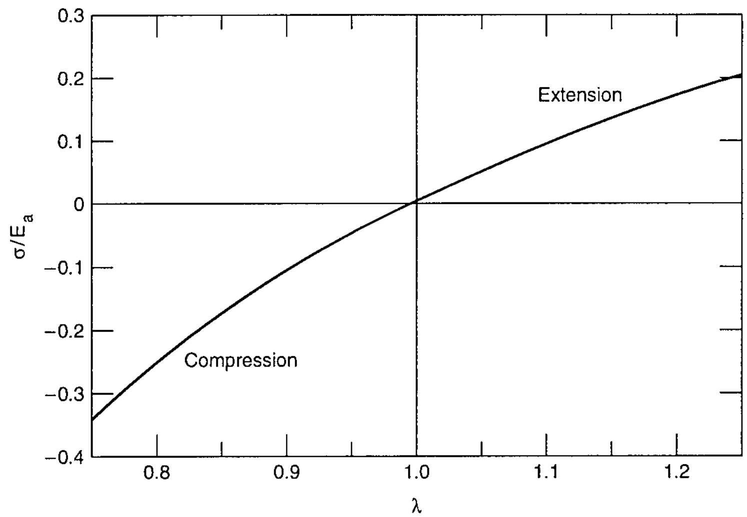
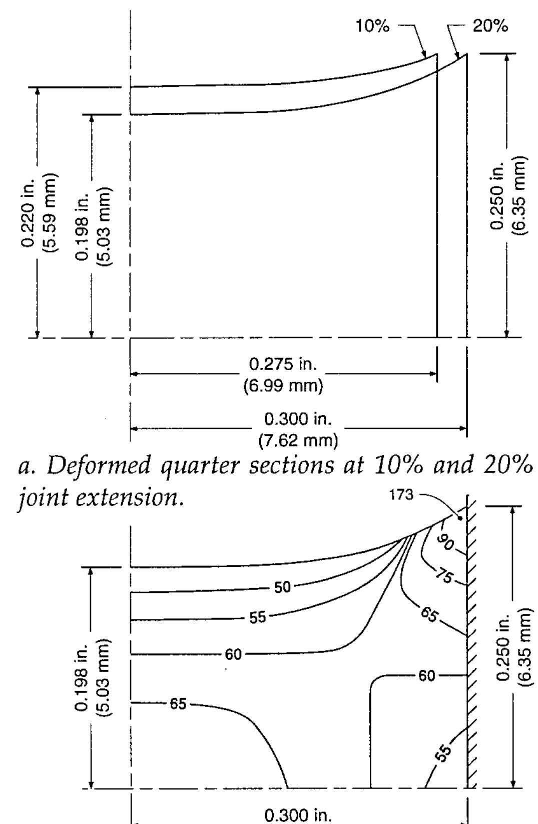


Figure 9. Approximation of the nominal stress–strain response of a butt joint seal in extension and compression. (From Gent and Lindley 1959.)

the ratio of the nominal stress to the apparent Young's modulus can be written as

$$\frac{\sigma}{E_a} = \frac{\lambda^{-2} - \lambda}{3}, \tag{4}$$

where σ is the nominal stress acting on the seal and λ is the extension ratio of the current joint width to the original joint width. The relation is depicted in Figure 9. Gent and Lindley illustrated with experimental results that the approximation reasonably represents the compression of vulcanized natural rubber blocks with d/w ratios from 0.36 to 1.7, and with lengths equal to w, to approximately 25% compression. These results, by the influence of the apparent modulus on the large deformation response, provide further elucidation of the influence of the shape factor on the stress of a seal. It should be noted, however, that the use of eq 4 implies the applicability of a strain energy function with the form of the first term in eq 1. Although this term provides a good representation of rubber constitutive behavior, it does not represent rubber behavior in general (Treloar 1974). Cook (1965a, 1965b) later considered the homogeneous rubber elasticity relation of eq 4 for sealant materials, but inappropriately used the equation directly for the inhomogeneous deformation of butt joint seal specimens without distinguishing between the material Young's modulus and the apparent Young's modulus, as shown to be necessary by Gent and Lindley (1959).



b. Maximum principal stress distribution at 20% joint extension.

Figure 10. Results of numerical analysis of a 1.2- × 1.2-cm silicone butt joint seal. (From Catsiff et al. 1970b.)

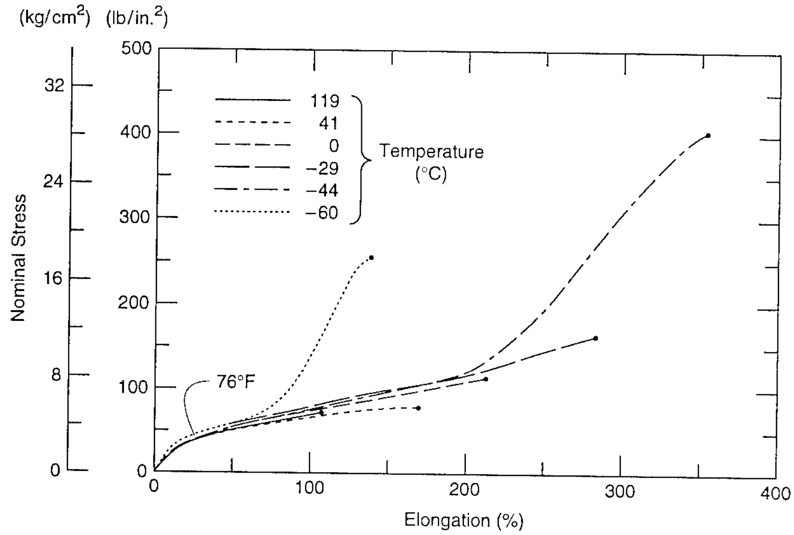


Figure 11. Karpati's (1972a) results showing the effect of temperature on the nominal stress–percentage elongation response of silicone butt joint seal specimens.

Rubber elasticity models have been used with finite-deformation numerical analysis techniques to model the large deformation behavior of seals. Figure 10 shows results generated by Catsiff et al. (1970b) using finite element approximations for plane strain sections of silicone butt joint seals. The stress distribution and deformed configurations in Figure 10 illustrate a quantitative prediction of the response, and demonstrate the insight into the response behavior that can be obtained through such analysis. In particular, the high stress level at the corner reveals the critical zone within the structure, and suggests that adhesive failure would likely occur in this area if failure stresses are reached. The use of these techniques requires an appropriate calibration of the hyperelastic material model, however, which has not always been the case. For example, Holland (1990) calibrated a hyperelastic model with results from structural property tests rather than material property tests, evidently presuming that the structural responses represented homogeneous behavior.

Other analysis techniques, particularly analytical solutions based on small-strain elasticity theory, have been developed to investigate the effect of the material volume change behavior on the stress distribution within a joint seal when the seal is constrained to have zero width change. Such techniques would apply to the response of a seal to thermal and other volume change mechanisms. Wu (1982) has reviewed these techniques.

Responses of model seals from experimental work on building and pavement sealants from several research programs are illustrated in Figures 11 through 16. These examples from the literature have been chosen to demonstrate the nature of the responses of seals formed from a variety of materials under a range of conditions. The first example is Karpati's (1972a) joint extension experiments showing the effect of temperature on silicone butt joint seal specimens with dimensions of 1.3 × 1.3 cm in the cross section and with a length of 5.1 cm. The material of the supporting bars was aluminum. The test results are depicted in Figure 11. As Karpati suggested, below 50% extension of the joint and 350 kPa (50 psi) of nominal stress, there was little effect of temperature upon the seal responses, except that slightly stiffer responses were observed at the −42°C (−44°F) and −51°C (−60°F) temperatures. For this material the effect of temperature was primarily evident at much higher deformations of the seals. This observation is consistent with the low glass transition temperature of silicone. The effect that the deformation rate has on the response is shown in Figure 12 for tests at −23°C (−10°F) and 22°C (72°F) (Karpati 1972b). Here is seen a more pronounced effect on the stiffness below 50% extension, relative to the negligible effect of temperature, with the higher deformation rates resulting in stiffer specimens. As a comparison, Karpati's (1973) results from polysulfide model seals are illustrated in Figure 13. Again results at two temperatures are shown (−34°C and 23°C), at the different deformation rates indicated, which in this case reflect a significant stiffening of the seal response from the higher

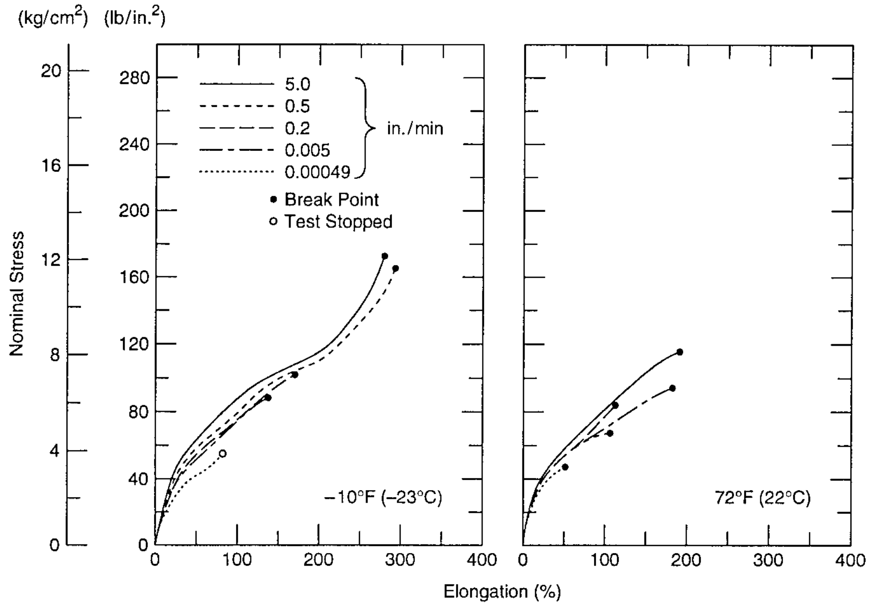


Figure 12. Karpati's (1972b) results showing the effect of deformation rate on the nominal stress–percent elongation response of silicone butt joint seal specimens.

to the lower temperature. Karpati reported that the polysulfide sealant material had a glass transition temperature of –46°C (–50°F). The results also show stiffer responses for the higher deformation rates.

Karpati did not conduct material property tests. She did, however, apply material property concepts of temperature and strain-rate dependence from the polymers field to interpret the responses of model structures (Karpati 1972c, 1973). Karpati recognized that the model seals have "an extremely complicated stress field" (Karpati 1972c), citing the work of Catsiff et al. (1970b), and chose the geometry of a single structure for her work. Although Karpati's results provide insight into the material behavior, as suggested by Catsiff et al. (1970a), it

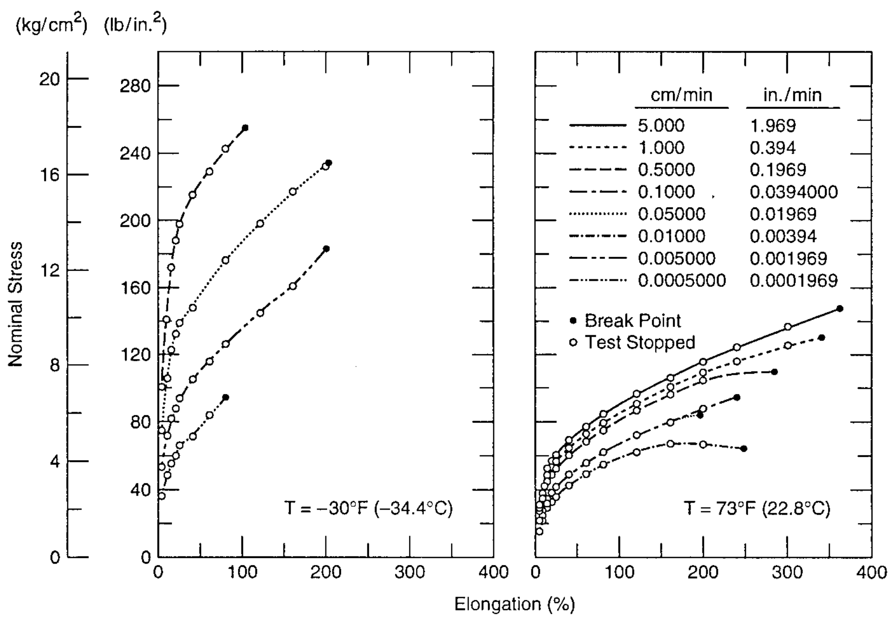


Figure 13. Karpati's (1972b) results showing the effect of deformation rate on the nominal stress–percentage elongation response of polysulfide butt joint seal specimens.

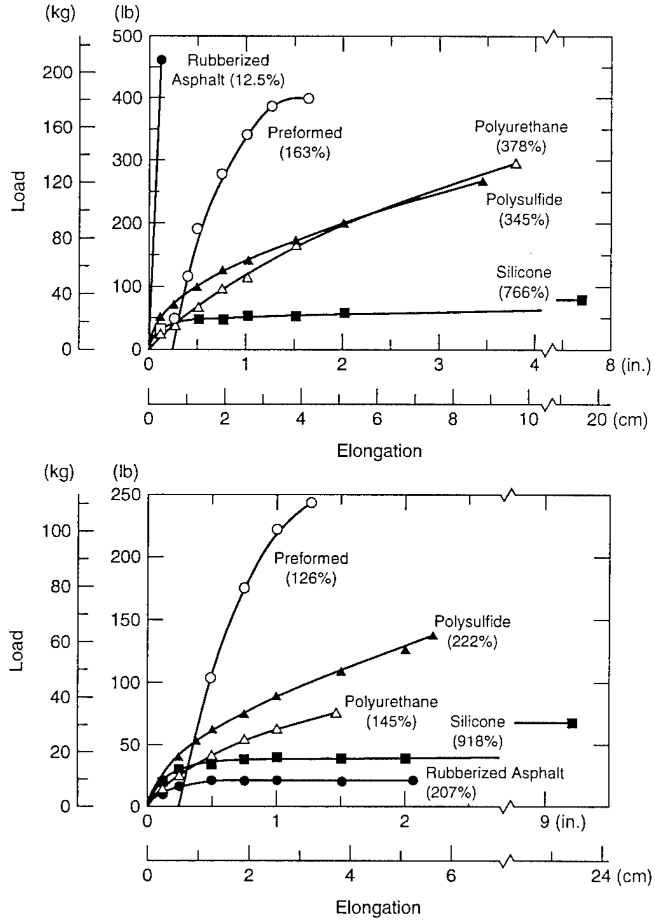


Figure 14. Results from constant rate of extension tests of butt joint seal specimens formed from various sealants, at –7°C (20°F) and 22°C (72°F). (From Collins et al. 1986.)

is not possible to extrapolate such results to quantitatively predict general structural behavior, i.e., the behavior of seals with different geometries and structural configurations.

Karpati's results illustrated in Figures 11–13 indicate the nominal loads and joint extensions at failure of the butt joint seals. A comparison of the results with the schematic illustration in Figure 4 for material specimens demonstrates the underlying influence of the strain rate and temperature dependence of the material on the butt joint seal response. In general the failures take place at high joint expansions relative to the requirements of a field joint. This is the desired behavior of a low modulus sealant; i.e., the flexibility of the seal causes stresses to remain below failure levels for expected joint movements.

Other examples are the experiments by Collins et al. (1986), which demonstrate the effect of temperature on the response of model seals. Results from the experiments are shown in Figure 14. The tests were constant rate of joint extension experiments using seal specimens with dimensions of 2.5 × 2.5 × 12.7 cm. The extension rate was 1.2 cm/min, and the test temperatures were –7°C (20°F), 22°C (72°F) and 54°C (130°F). Materials marketed as pavement sealants were used to form the model seals, and the material of the supporting bars was portland cement concrete. The materials are indicated on the figure together with the extension ratios at failure. Also shown in the graphs are the responses of a preformed compression seal.

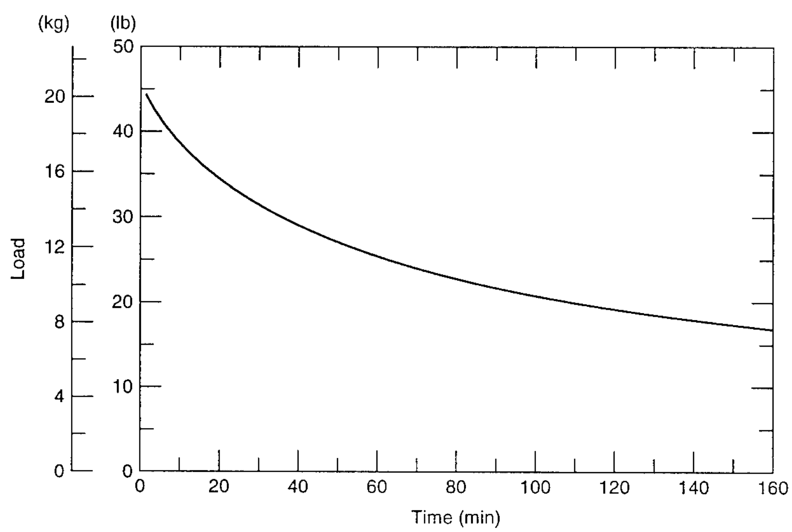


Figure 15. Cook's (1965a) results from step deformation tests of polysulfide butt joint seal specimens.

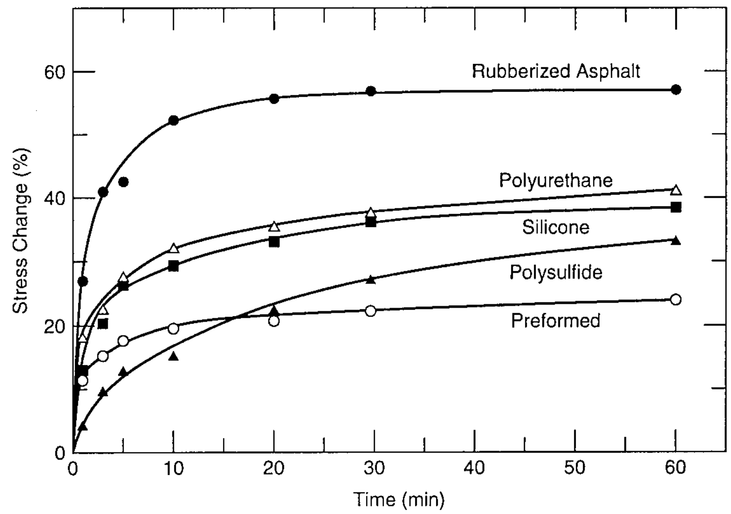


Figure 16. Results from step deformation tests of butt joint seal specimens formed from various sealants. (From Collins et al. 1986.)

The load and deformation responses shown in Figure 14, as well as secant stiffness values of the model seals for 50% extension reported by Collins et al. (1986), show that significant stiffening of the responses occurred at –7°C for all of the materials except the silicone sealant. The stiffening of the rubberized asphalt seal due to the temperature reduction was extreme.

Results from step deformation tests of polysulfide butt joint seal specimens performed by Cook (1965) are shown in Figure 15. The load vs. time curve in Figure 15 reflects the stress–relaxation material response and the viscous nature of the polysulfide sealant. Results from similar experiments reported by Collins et al. (1986) are shown in Figure 16. These tests were conducted at 22°C (72°F) using the materials of Figure 14 and the model seal geometry described above for the joint extension tests of Collins et al. (1986). The measurements were made after extending the model seals 50% at a deformation rate of 25 cm/min. The percent change in the nominal stress vs. time is shown in Figure 16. It is interesting to note that while all of the responses shown in this figure reveal viscous behavior, as suggested by Collins et al. some of the behavior is viscoelastic and some viscoplastic. Without unloading curves this distinction cannot be made, however.

SUMMARY AND RECOMMENDATIONS

The primary mechanical requirements of a pavement joint seal are that it respond elastically or viscoelastically to any thermally or load-induced movement of the joint without failure of the seal or the adhesive bond, and that it cure to a sufficient hardness and remain sufficiently hard so that it will not be damaged by indentation of harder objects. Because joint movements are often large, joint seals must be expected to withstand large deformations. Winter conditions are recognized as the most critical for a seal because of the possibility that failure stresses will be reached in the seal or at the adhesive interface as the joint opens and the material stiffens in response to the temperature reduction. For all conditions the ideal behavior of a pavement joint seal is that of an elastomer. As a result sealants have been formulated with a rubber or elastomer as a base material in order to have relatively low resistance to load at low temperatures.

Pavement joint sealants that include a rubber or elastomer as a base material are, in essence, elastomeric compounds, and should be considered as such for research and engineering applications. Although plastic behavior is observed in the response of some sealant compounds containing elastomers, in general these sealants are formulated and promoted to behave with rubber-like characteristics. To describe the mechanical properties of these sealants it is helpful to consider sealant behavior in the context of the behavior of rubbers and elastomers since the material response features of practical interest for sealing joints are clearly revealed, and since the elastomeric qualities that a seal displays when subjected to field loadings and conditions can be used to judge the effectiveness of the sealant. Implicit in any description of an elastomeric compound, however, is a temperature range for which rubber-like behavior occurs. As the temperature of an elastomer is decreased, its mechanical behavior changes until it behaves like glass. This is a phenomenon that can cause seals to stiffen during cold periods. Very few data exist in the literature or in manufacturers' specifications concerning sealant properties as a function of temperature, although in the rubber and polymers industry such material property data are routinely generated for evaluating the effectiveness of a material. Without such data, or without extensive practical experience, seal designers cannot independently know the temperature below which a sealant will perform inadequately. For a particular cold region application, performance tests conducted at a single low temperature, which is a typical condition implemented in standard test methods, do not in general provide enough information for an engineer to establish the effectiveness of a sealant.

Previous experimental studies of the mechanical behavior of joint and crack sealants have relied primarily on structural configuration performance tests rather than material property tests to obtain measures of the sealant response. Although structural configuration tests can reveal system properties, properties reflecting the stress and strain behavior of the material cannot be found from these tests. Structural tests are generally conducted using block-shaped model seal specimens constrained between parallel surfaces of a given substrate. These tests have been developed primarily to provide a basis for quantifying the capability of the seal to withstand the movements of seasonal joint opening and closing. There is confusion in the sealant literature regarding the nature of tests on model seals, however. Of greatest concern is that research test results of model seals are often reported as if a homogeneous material response rather than an inhomogeneous structural response has been measured. This lack of distinction between the response of the material and the response of the structure formed from the material has led to a conventional practice in which butt joint seal structures are tested not only to ascertain the behavior of a particular structure, but also to specify the behavior of the sealant material, and to do so without suggesting that the behavior is the apparent material behavior for the particular structure. Structural and experimental analysis conducted more than 30 years ago clearly showed that this practice can be misleading.

Structural analysis, for the most part, has been ignored by sealant researchers, although there have been recommendations within the sealant research community that conventional practices of structural mechanics be used to study and specify the behavior of sealants. In the related field of rubber and elastomers it is conventional practice to conduct material property tests, as a function of temperature, and to use the information obtained to conduct structural analysis. In all of structural engineering research it is also conventional to validate the results of analysis with tests of model structures. This classic framework should be applied in the research of sealants and joint seals, and should be followed to study sealants for cold climate applications. As indicated in this review, phenomenological theories of material behavior, material property tests, structural analysis methods and structural testing capabilities are available for adopting this framework. For the development of selection and design criteria for cold climate sealants and seals, this approach, as compared to the conventional performance testing approach, would be most efficient and productive.

LITERATURE CITED

ACI (1993) Guide to sealing joints in concrete structures, ACI 504R-90. In *ACI Manual of Concrete Practice. Part 5.* Detroit, Michigan: American Concrete Institute.

ASTM (1991a) Standard definitions of terms relating to building seals and sealants. C 717-87a. *Annual Book of ASTM Standards*, Vol. 4.07. Philadelphia, Pennsylvania: American Society for Testing and Materials.

ASTM (1991b) Standard terminology relating to rubber. D 1566-88. *Annual Book of ASTM Standards*, Vol. 9.01. Philadelphia, Pennsylvania: American Society for Testing and Materials.

ASTM (1991c) Standard practice for determining and reporting dynamic mechanical properties of plastics. D 4065-82. *Annual Book of ASTM Standards*, Vol. 8.03. Philadelphia, Pennsylvania: American Society for Testing and Materials.

ASTM (1991d) Standard test methods for rubber properties in tension. D 412-87. *Annual Book of ASTM Standards*, Vol. 8.01. Philadelphia, Pennsylvania: American Society for Testing and Materials.

ASTM (1991e) Standard methods of testing joint sealants, hot-poured, for concrete and asphalt pavements. D 3407-78. *Annual Book of ASTM Standards*, Vol. 4.03. Philadelphia, Pennsylvania: American Society for Testing and Materials.

ASTM (1991f) Standard guide for use of elastomeric joint sealants. C 962. *Annual Book of ASTM Standards*, Vol. 4.07. Philadelphia, Pennsylvania: American Society for Testing and Materials.

Beech, J.C. (1985) Test methods for the movement capability of building sealants. The "state of the art." *Materials and Structures*, **18**(108): 473–481.

Bueche, A.M. and J.P. Berry (1959) The mechanisms of polymer fracture. In *Fracture* (B.L. Averbach et al., Ed.). Cambridge, Massachusetts: MIT Press.

Catsiff, E.H., R.F. Hoffman and R.T. Kowalewski (1970a) Predicting joint sealant performance of elastomers by computer simulation. I. Justification of method. *Journal of Applied Polymer Science*, **14**: 1143–1158.

Catsiff, E.H., R.F. Hoffman and R.T. Kowalewski (1970b) Predicting joint sealant performance of elastomers by computer simulation. II. Results in simple extension and compression. *Journal of Applied Polymer Science*, **14**: 1159–1178.

Chaloub, M.S. and J.M. Kelly (1991) Analysis of infinite-strip-shaped base isolator with elastomer bulk compression. *Journal of Engineering Mechanics, ASCE*, **117**(8): 1791–1805.

Collins, A.M., W.D. Mangum, D.W. Fowler, A.H. Meyer and D.P. Whitney (1986) Improved methods for sealing joints in portland cement concrete pavements. Report No. FHWA/TX-87+385–1. Federal Highway Administration, Washington, D.C.

Cook, J.P. (1965a) A study of polysulfide sealants for joints in bridges. *Highway Research Record*, **80**: 11–35.

Cook, J.P. (1965b) Effects of specimen length on laboratory behavior of sealants. *Highway Research Record*, **80**: 74–78.

Eisenberg, A. (1984) The glassy state and the glassy transition. In *Physical Properties of Polymers*, p. 1–26. Washington, D.C.: American Chemical Society.

Finney, R.H. and A. Kumar (1988) Development of material constants for nonlinear finite-element analysis. *Rubber Chemistry and Technology*, **61**(5): 879–891.

Gent, A.N. and P.B. Lindley (1959) The compression of bonded rubber blocks. In *Proceedings of the Institute of Mechanical Engineers*, **173**(3): 111–117.

Gent, A.N. and A.A. Meinecke (1970) Compression, bending, and shear of bonded rubber blocks. *Polymer Engineering and Science*, **10**(1): 48–53.

Green, A.E. and J.E. Adkins (1960) *Large Elastic Deformations*. London: Oxford University Press.

Hearle, J.W.S. (1982) *Polymers and Their Properties, Volume 1: Fundamentals of Structure and Mechanics*. New York: Halsted Press.

Hibbitt, Karlsson and Sorenson, Inc. (1989) *Abaqus User's Manual*. Version 4.8. Providence, Rhode Island.

Holland, T.J. (1990) Finite element study of joint seals in portland cement concrete pavements. NCEL Technical Note N-1806. Naval Civil Engineering Laboratory. Port Hueneme, California.

Immergut, E.H. and H.F. Mark (1965) Principles of plasticization. In *Plasticization and Plasticizer Processes. Advances in Chemistry, Series 48*. American Chemical Society, Washington, D.C., 1-26.

Karpati, K.K. (1972a) Mechanical properties of sealants. I. Behavior of silicone sealants as a function of temperature. *Journal of Paint Technology*, **44**(565): 55–62.

Karpati, K.K. (1972b) Mechanical properties of sealants. II. Behavior of a silicone sealant as a function of rate of movement. *Journal of Paint Technology*, **44**(569): 58–65.

Karpati, K.K. (1972c) Mechanical properties of sealants. III. Performance testing of silicone sealants. *Journal of Paint Technology*, **44**(571): 75–85.

Karpati, K.K. (1973) Mechanical properties of sealants. IV. Performance testing of two-part polysulfide sealants. *Journal of Paint Technology*, **45**(580): 49–57.

Karpati, K.K. (1980) Weathering of silicone sealant on strain-cycling exposure rack. *Adhesives Age*, **23**(11): 41–47.

Karpati, K.K. (1989) Performance of polyurethane sealants on a strain-cycling exposure rack. *Materials and Structures*, **22**: 60–63.

Karpati, K.K., K.R. Solvason and P.J. Sereda (1977) Weathering rack for sealants. *Journal of Coatings Technology*, **49**(626): 44–47.

Kearsley, E.A. and L.J. Zapas (1980) Some methods of measurement of an elastic strain-energy function of the Valanis-Landel type. *Journal of Rheology*, **24**(4): 483–500.

Lynch, L.N. (1990) *Asphalt Crack Repair Field Manual* (Draft). NAVFAC MO-102.6. Alexandria, Virginia: Naval Facilities Engineering Command.

Malvern, L.E. (1969) *Introduction to the Mechanics of a Continuous Medium*. New Jersey: Prentice Hall.

Mark, J.E. (1982) Rubber elasticity. *Rubber Chemistry and Technology*, 55(4): 1123–1136.

McKenna, G.B. and L.J. Zapas (1986) On the small strain behavior of peroxide crosslinked natural rubber. *Rubber Chemistry and Technology*, **59**(1): 130–137.

Minkarah, I., J.P. Cook and J.F. McDonough (1982) Magnitude of horizontal movement in jointed concrete pavements. *Transportation Research Record*, no. 821, 61–67.

Nashif, A.D. and T.M. Lewis (1991) Data base of the dynamic properties of materials. *Sound and Vibration*, **25**(7): 14–25.
Nolle, A.W. (1950) Dynamic mechanical properties of rubberlike materials. *Journal of Polymer Science*, **5**(1): 1–54.
Panek, J.R. and J.P. Cook (1984) *Construction Sealants and Adhesives, Second Edition*. New York: John Wiley.
Penn, R.W. and E.A. Kearsley (1976) The scaling law for finite torsion of elastic cylinders. *Transactions of the Society of Rheology*, **20**(2): 227–238.
Rivlin, R.S. (1956) Large elastic deformations. In *Rheology, Volume 1*. (F.R. Eirich, Ed.). New York: Academic Press.
Rivlin, R.S. and D.W. Saunders (1951) Large elastic deformations of isotropic materials. VII. Experiments on the deformation of rubber. *Philosophical Transactions of the Royal Society of London*, No. A243, 251–288.
Sandberg, L.B. and A.E. Rintala (1990) Resistance of structural silicones to creep rupture and fatigue. In *Building Sealants: Materials, Properties, and Performance*. ASTM STP 1069, p. 7–21 (T.F. O'Conner, Ed.). Philadelphia, Pennsylvania: American Society for Testing and Materials.
Shisler, F.W., III and J.M. Klosowski (1990) Sealant stresses in tension and shear. In *Building Sealants: Materials, Properties, and Performance*. ASTM STP 1069, p. 95–107. (T.F. O'Conner, Ed.). Philadelphia, Pennsylvania: American Society for Testing and Materials.
Smith, T.L. and P.J. Stedry (1960) Time and temperature dependence of the ultimate properties of an SBR rubber at constant elongations. *Journal of Applied Physics*, **31**(11): 1892–1898.
Spells, S. (1987) Silicone sealants for use in airfield applications. *American Concrete Institute, SP-94*. **2**: 805–816.
Tons, E. (1959) A theoretical approach to design of a road joint seal. *Concrete Pavement: Subbase and Joint Construction*. Highway Research Board, Bulletin 229, 20–53.
Treloar, L.R.G. (1974) The elasticity and related properties of rubbers. *Rubber Chemistry and Technology*, **47**: 625–696.
Treloar, L.R.G. (1975) *The Physics of Rubber Elasticity, Third Edition*. Oxford: Clarendon Press.
Ward, I.M. (1983) *Mechanical Properties of Solid Polymers, Second Edition*. New York: John Wiley.
Williams, J.G. (1984) *Fracture Mechanics of Polymers*. New York: Halsted Press.
Wu, S. (1982) *Polymer Interface and Adhesion*. New York: Marcel Dekker.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	May 1995	

4. TITLE AND SUBTITLE

Sealants and Cold Regions Pavement Seals: A Review

5. FUNDING NUMBERS

PE: 6.27.84A
PR: 4A762784AT42
TA: CP
WU: K01

6. AUTHORS

Stephen A. Ketcham

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

U.S. Army Cold Regions Research and Engineering Laboratory
72 Lyme Road
Hanover, New Hampshire 03755-1290

8. PERFORMING ORGANIZATION REPORT NUMBER

CRREL Report 95-11

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Office of the Chief of Engineers
Washington, D.C. 20314-1000

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

Available from NTIS, Springfield, Virginia 22161

12b. DISTRIBUTION CODE

13. ABSTRACT (*Maximum 200 words*)

A pavement joint seal prevents the passage of liquids into the pavement base and the intrusion of solids into the joint. The primary mechanical requirements of a pavement seal are that it respond elastically or viscoelastically to any movement of the joint without failure and that it withstand indentation of hard objects like rocks. Because pavement joint movements and seal deformations can be large, elastomeric sealants are often used to form seals. Winter conditions are recognized as the most critical for a seal because of the possibility that failure stresses will be reached as the joint opens to a maximum and the material stiffens in response to the temperature reduction. This report reviews the specific problems and requirements that cold climates create for the performance of elastomeric seals. Emphasis is placed on the material response behavior that can lead to failure of a seal. In an attempt to clarify the mechanics of sealant and seal performance associated with low-temperature pavement applications and to address the issue of low-temperature stiffening that should be a dominant factor in the selection of a sealant, this report presents background information on the formulation and mechanical properties of elastomeric seal materials and the structural behavior of field-molded joint and crack seals.

14. SUBJECT TERMS

Cold regions
Elastomers
Pavement seals
Sealants

15. NUMBER OF PAGES

28

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL