

**SEALING OF
SMALL MOVEMENT BRIDGE EXPANSION JOINTS**

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16. Abstract Sealing of bridge expansion joint systems is important to protect the structural components below the joint from damage due to water, salt, and other roadway debris. A new elastomeric foam-type joint sealant has been developed for sealing small-movement bridge expansion joints. Laboratory tests including tension, compression, shear, bonding, salt water immersion, temperature sensitivity, compression recovery, creep, stress relaxation, cure rate, tack time, and water tightness were performed on this newly developed sealant to assess its mechanical and material characteristics. In addition, loading-unloading behavior in tension and compression and effects of exposure to outdoor condition for 6.5 months period on its engineering properties were investigated. Similar tests were also performed on a currently available commercial bridge joint sealant material for comparison purposes. The new silicone foam sealant showed an increase in volume by about 70 % after the mixing of sealant components. The test results indicated lower stiffness, greater extensibility, and better bonding associated with the foam sealant compared to the commercial sealant. Foam sealant showed more resistant to fatigue with tensile deformation cycles and its stress relaxation rate was greater than that of commercial sealant. The tack and cure time for foam sealant were small and no leakage was observed through the sealant and joint interface. The sealant also did not exhibit any physical deterioration during prolonged exposure to natural weathering elements; however it appeared to stiffen which might be due to oxidation and continuous sealant cure.					
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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol	When You Know	Multiply By	To Find	Symbol
LENGTH								
in	inches	25.4	millimeters	mm	mm	0.039	inches	in
ft	feet	0.305	meters	m	m	3.28	feet	ft
yd	yards	0.914	meters	m	m	1.09	yards	yd
mi	miles	1.61	kilometers	km	km	0.621	miles	mi
AREA								
in ²	square inches	645.2	square millimeters	mm ²	mm ²	0.0016	square inches	in ²
ft ²	square feet	0.093	square meters	m ²	m ²	10.764	square feet	ft ²
yd ²	square yards	0.836	square meters	m ²	m ²	1.195	square yards	yd ²
ac	acres	0.405	hectares	ha	ha	2.47	acres	ac
mi ²	square miles	2.59	square kilometers	km ²	km ²	0.386	square miles	mi ²
VOLUME								
fl oz	fluid ounces	29.57	milliliters	mL	mL	0.034	fluid ounces	fl oz
gal	gallons	3.785	liters	L	L	0.264	gallons	gal
ft ³	cubic feet	0.028	cubic meters	m ³	m ³	35.71	cubic feet	ft ³
yd ³	cubic yards	0.765	cubic meters	m ³	m ³	1.307	cubic yards	yd ³
NOTE: Volumes greater than 1000 l shall be shown in m ³ .								
MASS								
oz	ounces	28.35	grams	g	g	0.035	ounces	oz
lb	pounds	0.454	kilograms	kg	kg	2.202	pounds	lb
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")	Mg (or "t")	1.103	short tons (2000 lb)	T
TEMPERATURE (exact)								
°F	Fahrenheit temperature	5(F-32)/9 or (F-32)/1.8	Celsius temperature	°C	°C	1.8C + 32	Fahrenheit temperature	°F
ILLUMINATION								
fc	foot-candles	10.76	lux	lx	lx	0.0929	foot-candles	fc
fl	foot-Lamberts	3.426	candela/m ²	cd/m ²	cd/m ²	0.2919	foot-Lamberts	fl
FORCE and PRESSURE or STRESS								
lbf	pound-force	4.45	newtons	N	N	0.225	pound-force	lbf
lbf/in ²	pound-force per square inch	6.89	kilopascals	kPa	kPa	0.145	pound-force per square inch	lbf/in ²

* SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.

(Revised September 1993)

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1. INTRODUCTION

1.1 BACKGROUND

Bridges are continually moving. The movements could be due to temperature and humidity changes; creep, shrinkage and cyclic effects; axial and flexural strains arising from dead and live loads and prestressing; dynamic load effects including impact, vehicle braking and lurching, centrifugal forces; and long-term movements such as those caused by settlement and earth pressure (Lee, 1994). For the bridge to function as intended, it must be capable of accommodating all such movements. The total combined motion of a bridge is deceptively slow; however, forces involved are tremendous. For a 80-foot simple span steel bridge with W36 x 210 longitudinal stringers, the force generated at one bearing, should its movement be impeded because of a 40°F temperature change, would be over 466 kips from the beam alone (Mumber, 1993). So it is clearly evident that providing a means to accommodate movements is extremely important to prevent the development of secondary stresses in the bridge superstructure.

Movement is usually accommodated by bridge bearings and deck expansion joint system; however, because bridge bearings are often sources of trouble, many bridges are designed so that the entire structure takes care of movement without bearings. This is done by making bridge piers flexible allowing for movements in the abutments and being sure the approach pavement is not so rigid that the bridge is not allowed to expand and contract as temperature dictate. When these methods cannot be used, however, expansion joint details must be provided to allow the bridge free movement (NCHRP, 1977). A properly functioning bridge deck joint accommodates the horizontal and vertical movements of the structure while providing smooth rideability, low noise level, wear resistance and resistance to damage by

snowplow equipment. In addition, bridge joints should allow easy maintenance, repair, and replacement. Bridge deck joints fall into two broad categories: open joints and closed joints.

Open joints permit cyclic and long-term movement and support traffic. They may include armor protection against damage to concrete edges exposed to traffic. The most common open expansion joints include butt joints either with or without armor facing, sliding plate joints, and finger joints. The major disadvantage of these joints is that they allow water and corrosive contamination to pass through them. Therefore, most of the transportation agencies currently avoid the use of open joints because of this undesirable feature (Purvis, 2003). Draining troughs below the open joints may help ensure that water and debris fall clear of the supporting structures. However, they produce other set of problems, the most common ones being the filling up of the trough with the dirt and debris and continuous maintenance efforts needed to keep them clean and properly functioning.

Sealed or closed expansion joints provide barriers preventing runoff water and deicing chemicals from passing through the joint on to bearing and substructure elements below the bridge deck. Water and deicing chemicals have a detrimental impact on overall structural performance by accelerating degradation of bridge deck, bearing, and substructure elements (Chen and Duan, 2000). Several types of sealed joint systems have been developed in an attempt to achieve a joint seal design that would be both effective and durable. Most widely used among them are hot/cold poured seals, compression seal, strip seal, and modular joints. These traditional methods of expansion joints have, however, failed to show durability and longevity and have created much doubt in bridge engineering community as to the viability of currently in use sealed joint systems.

A number of observations and reports indicate that many deck expansion joint systems (Both open and closed joints) have performed poorly [for example, see References: Benson (1986), Chang and Lee (2002), Dahir and Mellott (1985), Frederick (1984), Hamilton (1985), Voigt and Yrjanson (1992)]. Many have failed to provide water leak proof conditions. A survey conducted by the Federal Highway Administration (FHWA) (Fincher, 1983) indicated that, in a five year evaluation period, over 60% of the joints were leaking water and the remaining 40% were experiencing problems that would shorten their service lives. Where deicing salts are used, leakage of joints promotes the spread of damaging chloride-laden liquid. Impregnation damage of concrete by chloride is known to be one of the leading causes of deterioration in reinforced concrete bridges. Under traffic, some of the joint systems (e.g., finger plate and sliding plate) are objectionably noisy, and the surfaces of some systems (e.g., compression seal and strip seal) are prone to damage by snowplow blades (Linfante and Castro, 1977).

Because of the problems associated with leaking joints, the concept of construction of bridges with continuous superstructure (without intermediate joints) or integral abutment (no deck joints at abutments) has been introduced in the bridge industry (Burke 1989; Lee 1994). The use of such constructions is usually justified by the fact that they lead to more economical bridge design by elimination of costly joints and bearings and they are relatively easier to repair as the problems of expansion joints are moved from the bridge to its approaches. However, it is also noted that behavior of such joint- free bridges are still not completely understood and designs are cumbersome (Thippeswamy et al, 2002)

1.2 RESEARCH MOTIVATION

Despite the problems associated with maintenance-prone leaking joints, most existing bridges have expansion joints, and transportation agencies are concerned with keeping joints functioning properly and water tight. For new construction, many transportation agencies are willing to eliminate deck joints from their bridges. This is achieved by some modifications in the design (e.g., continuous superstructure and integral abutment) which transfers the problems that take place at joint to another location that might be off the bridge. Despite the growing tendency of using jointless bridges among transportation agencies, expansion joints most likely will still continue to remain as an integral part of many new bridge structures. It is in recognition of this fact and the limited success achieved with presently used joint sealing systems that this research study was undertaken as an attempt to develop a new seal for small movement expansion joints that would be economical, easy to install and maintain, and would accommodate movements over a reasonable design life while remaining watertight. The new bridge sealant would be applicable for the use in both new construction as well as rehabilitation work of existing bridge structures.

1.3 PROJECT OBJECTIVE

The main objective of the research reported in this thesis was to develop an effective and durable sealing system for small movement bridge expansion joints which can accommodate total expansion and contraction movements up to 45 mm while preventing the passage of water, deicing salts, and other road side contaminants through the joint on to the bridge bearings and substructure components and conduct a series of laboratory tests to

evaluate the performance and hence, ascertain its suitability for the real life application. More specifically the research objective can be summarized in following tasks:

- I. To conduct a thorough literature search to identify and evaluate the existing types of expansion joint systems currently being employed by transportation agencies in North America
- II. To determine factors influencing the successful performance of currently in use joint sealing systems and provide their relative performance information
- III. To develop a silicone based polymeric material as a potential bridge joint sealant in the laboratory. The newly developed sealant should be economical, easy to install and repair, and durable
- IV. To conduct a wide variety of tests to assess the newly developed sealant's mechanical and material properties. Laboratory tests proposed to be conducted included tension, compression, shear, bonding, salt water immersion, temperature sensitivity, compression recovery, creep, stress relaxation, cure rate, tack time, and water tightness test
- V. To prepare a final project report that contains research results with recommendations for phase II (Demonstration and Monitoring Phase) and that incorporates comments from the NETC Technical Committee.

2. REVIEW OF BRIDGE EXPANSION JOINTS

2.1 BRIDGE JOINTS: GENERAL DESIGN CRITERIA

The specifications for bridge joints are summarized in Section 14 in AASHTO LRFD Bridge Design Specifications (2004). These specifications are to be followed while selecting and designing an appropriate expansion bridge joint. State transportation agencies use AASHTO specifications, with modifications based on their experience and preferences. Some factors affecting the design and selection of a joint are listed below (Purvis, 2003):

(a) Movement range, (b) Bridge span, (c) Type of bridge, (d) Joint performance and previous experience, (e) Durability, (f) Maintenance requirements, (g) Bridge alignment, (h) Joint details at curbs, concrete barriers, or deck edges, (i) Initial cost, (j) Climate conditions (k) Expected joint life (l) Installation time, (m) Life-cycle costs, (n) Type of bridge supports, and (o) Service level.

Movement range is the chief concern when designing and specifying a particular expansion joint. Expansion joints accommodate movements produced by concrete shrinkage and creep, post-tensioning, thermal variations, dead and live loads, wind and seismic loads, and structure settlements. Concrete shrinkage, post-tensioning shortening, and thermal variations are generally taken into account explicitly in design calculations. Because of uncertainties in predicting, and the increased costs associated with accommodating large displacements, seismic movements are usually not explicitly included in calculations but where significant movement is important to the proper function of bridge elements (such as seismic isolation bearings), the movement due to seismic forces shall be accommodated in the design of joints. Finally, it may be worthwhile for bridge designers to consider the performance of expansion joint during lesser intensity seismic events (Gloyd, 1996).

Expansion joints should be designed to accommodate all concrete shrinkage occurring after their installation. For unrestrained concrete, ultimate shrinkage strain (β) after installation may be estimated as 0.0002 (Washington State Department of Transportation (DOT), 2005). Shrinkage shortening of the bridge deck, Δ_{shrink} , in mm, is calculated as

$$\Delta_{shrink} = (\beta)(\mu)(L_{trib})(1000mm / m) \quad \text{-----}(1)$$

Where,

L_{trib} = tributary length of structure subject to shrinkage; m

β = ultimate shrinkage strain after expansion joint installation; estimated as 0.0002
in lieu of more refined calculations

μ = factor accounting for restraining effect imposed by structural elements installed before slab in cast. External restraint to concrete shrinkage is often provided by the supports of a structural member and by the adjacent structure. The degree of restraint provided by various supporting systems is incorporated by factor μ in Eqn. (1). $\mu = 0.0$ for steel girders, 0.5 for precast prestressed concrete girders, 0.8 for concrete box girders and T-beams, 1.0 for flat slabs.

Thermal displacements are calculated using the maximum and minimum anticipated bridge deck temperatures. These extreme values are functions of the geographic location of the structure and the bridge type. For example, the temperature range used by Department of Transportation for the calculation of thermal movement of deck joints is based on a mean low temperature of -23° C and a mean high temperature of +43° C (Connecticut DOT, 2003). Thermal movement, Δ_{temp} , in mm, is calculated as (Washington State DOT, 2005)

$$\Delta_{temp} = (\alpha)(L_{trib})(\delta T)(1000mm / m) \quad \text{-----} (2)$$

Where, α = coefficient of thermal expansion; 0.000011 m/m/°C for concrete and 0.000012 m/m/°C for steel

L_{trib} = tributary length of structure in meter subject to thermal variation

δT = temperature variation in °C

Any other predictable movements following joint installation, such as concrete post-tensioning shortening and creep, should also be included in the design calculations.

2.2 TYPES OF BRIDGE JOINTS AND THEIR ADVANTAGES AND DISADVANTAGES

Expansion joints fall into three broad categories depending upon the amount of movement accommodated; (a) Small movement range joints encompass all systems capable of accommodating total motion ranges of up to about 45 mm, (b) Medium movement range joints include systems accommodating total motion ranges between about 45 mm and about 130 mm, and (c) Large movement range joints accommodate total motion ranges in excess of about 130 mm. These delineated ranges are somewhat arbitrary in that some systems can accommodate movement ranges overlapping these broad categories (Chen and Duan, 2000).

2.2.1 Small Movement Joints

Most common small movement joints include butt joint, sliding plate joint, compression seal joint, asphaltic plug joint, and poured seal joint. Various features of these joints are briefly presented below.

2.2.1.1 Butt Joint

Butt joint is commonly used for movements less than 25 mm (1 in.). The opening is provided between two rigid deck slabs with no provision for smooth transition of traffic between adjacent edges of the deck. They can be built with or without metal armoring angles as shown in the Fig. 1 (Burke, 1989). A metal angle is typically embedded to protect the top edge of both sides of the joint from spalling or raveling due to their exposure to continuous vehicular impacts.

As the butt joint does not provide barrier against water and debris, their use is precluded in geographical areas where deicing chemicals are used. Another disadvantage with this type of joint system is that over time, the angles may become dislodged due to the fatigue of anchor attachments thus creating a traffic hazard.

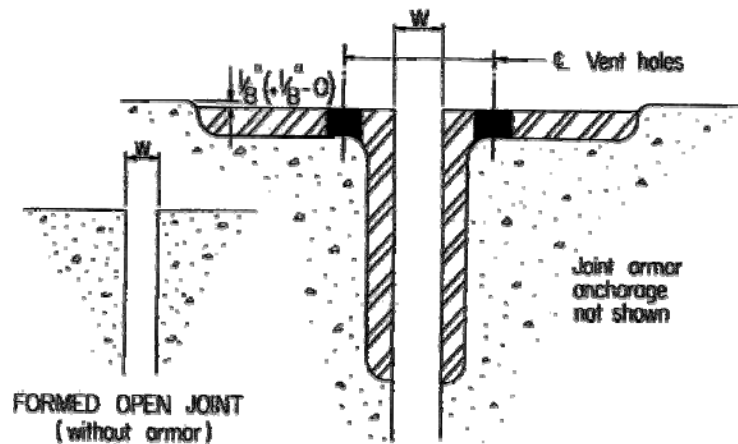


Figure 1. Butt joint.

2.2.1.2 Sliding Plate Joint

Steel sliding plates, shown in Fig.2 (Washington State DOT, 2005) have been used extensively in the past for expansion joints in both concrete and timber bridge decks. They

are used for movements from 25 to 75 mm (1 to 3 in.) and bridge lengths between joints of about 110 m (350 ft.). They are structurally simple and reasonable in cost. As seen in the Fig. 2, two overlapping steel plates are attached to the bridge deck, one on each side of the expansion joint opening. They are generally installed so that the top surfaces of the plates are flush with the top of the bridge deck. The plates are generally bolted to timber deck panels or embedded with steel anchorages in to a concrete deck. Standard steel sliding plates do not generally provide an effective seal against intrusion of water and deicing chemicals into the joint and on to substructure elements, but it does prevent most debris from passing through the opening.

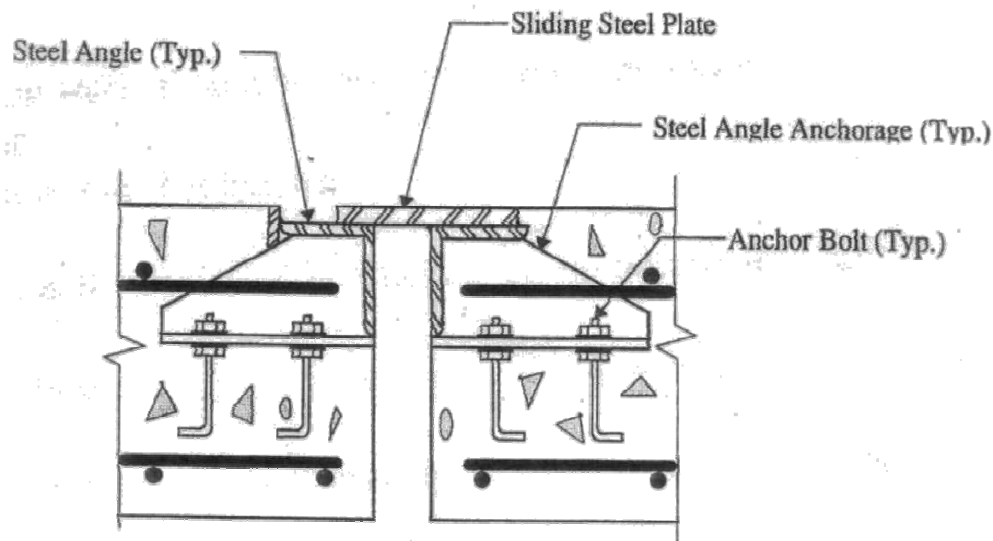


Figure 2. Sliding plate joint.

Sliding plate joints are usually limited to horizontal movements and their use is precluded where differential vertical movements can occur at joints. It is common for plates to loosen over time. Improperly placed and exposed plates bend, warp and break off from

their anchorages due to impact of heavy wheel loads and create a safety hazard (Hill and Shirole, 1984). Another poor feature of this joint is that the plates need to be adjusted periodically to reduce noise levels. Due to their unsatisfactory performance, other types of joints have replaced these joints in most places.

2.2.1.3 Compression Seal Joint

Compression seals, shown in Fig. 3 (Washington State DOT, 2005), are continuous elastomeric sections, typically with extruded internal web systems, installed within an expansion joint gap to seal the joint effectively against water and debris infiltration (Chen and Duan, 2000.) They can accommodate movements from 5 mm to 60 mm (0.25 in. to 2.5 in.). The joint face may or may not be strengthened with armor angles or polymer concrete header material. Compression seals are held in place by mobilizing friction against adjacent vertical joint faces. To help fill the voids between the seal and abutting surface, a moisture-curing polyurethane material with 75 percent solids content is used. Design philosophy requires that that seal must always be in compression to ensure that it stays in place and remains watertight. To minimize slippage and maximum compression seal performance, a joint may be formed narrower than the design width, then sawcut immediately prior to compression seal installation.

Elastomeric compression seals are versatile, relatively inexpensive and easy to replace. They have been found suitable for bridge application by many transportation departments, and are given very high ratings by these departments; however, other departments have abandoned their use entirely (Purvis, 2003). Agencies such as New York and Illinois, report that these are effective seals that require minimal maintenance with a

reasonable life span. Others such as Louisiana and Colorado, report unreliable performance. These seals are very much susceptible to damages from snowplows, debris, and traffic. For wider joints, it is difficult to ensure the adherence of the seal to the sides of the joint. Over time, the compression seal gradually loses its capability to retain its initial compression recovery due to loss of resilience and becomes brittle. This leads to leakage of water in to the bridge substructure through joint-seal interface causing accelerated deterioration of the substructure, bearings, and superstructure beams under the joint (Fig. 4; Ohio DOT, 2003).

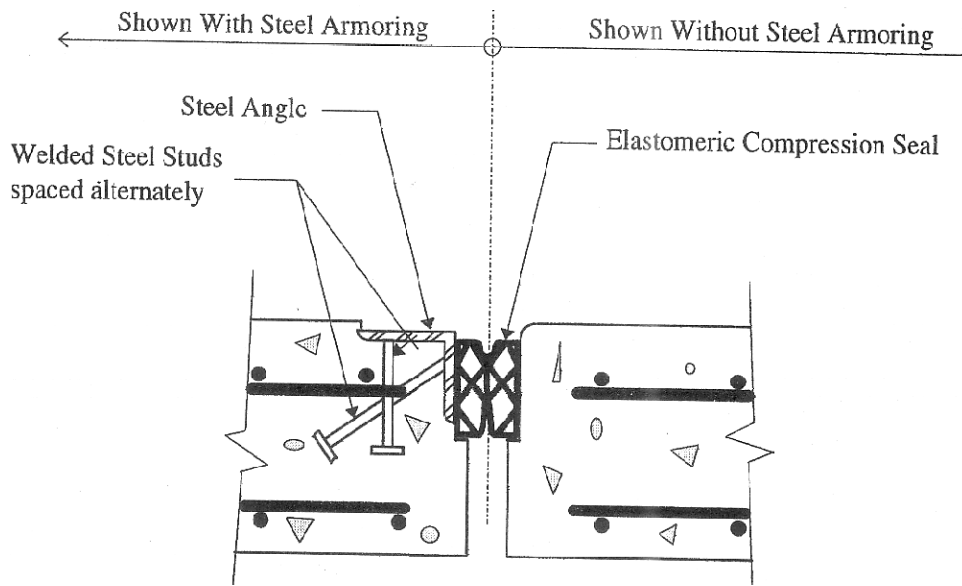


Figure 3. Compression seal.



Figure 4. Compression seal leakage.

2.2.1.4 Asphaltic Plug Joints

Asphaltic plug joint (APJ) is the most popular joint sealing system in New England transportation departments. The system is becoming popular with agencies in other parts of the country as well. Movement capacity of such joint is less than 50 mm (2 in.). Typical components of the joint are shown in Figure 5 (Washington State DOT, 2005).

It consists of a blockout 570 mm wide by 60 mm (minimum) deep (20 in. x 2in.). A closed cell, heat resistant backer rod is placed in the joint below the blockout. The joint is filled above the backer rod with polymer modified asphalt binder material (PMA), and a traffic bearing steel plate 230 mm (8 in.) wide by 6 mm (0.25 in.) thick is centered over the joint, bridging the opening, for its entire length. The blockout is filled with clean, dry, open-graded aggregates coated with the asphalt binder. After placement material is consolidated with a vibrating plate compactor and binder material is poured over the top of the compacted material to fill the voids.

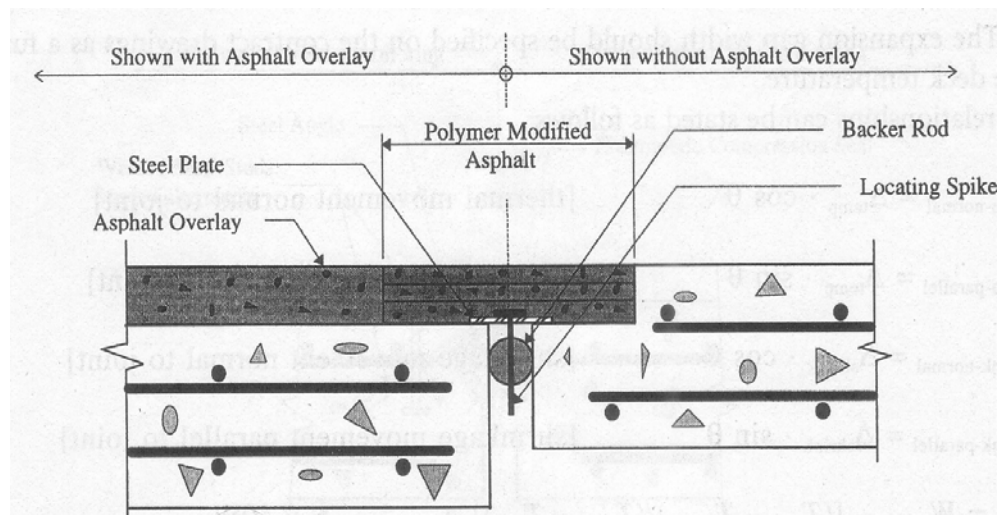


Figure 5. Asphaltic Plug Joint.

The primary advantage of this system is ease of installation and repair. In addition, it provides smooth and seamless roadway surface to the traffic. There is no debris collection atop the joint and they provide watertight and snowplow proof expansion joints. The major disadvantage of the system is that it is not effective method of sealing vertical joints or skewed joints. At locations with very high temperature, PMA material softens and creeps, which leads to wheel rutting and migration of binder from blockout [Fig. 6 (Ohio State DOT, 2003)]. Similarly, cracking of PMA occurs in very cold weather. Daily and seasonal temperature variations are stress inducing events for the APJ material. If the relaxation of the APJ material is not sufficient, the significant stresses are developed in the joint causing crack at joint-to-pavement interface (Bramel et al, 2000). Figure 7 (Ohio State DOT, 2003) shows a section coming out of the failed plug joint.



Figure 6. Material flowing on to adjacent pavements.



Figure 7. Section of failed joint.

2.2.1.5 Poured Sealed Joints

Durable low-modulus sealants, poured cold to provide watertight expansion joint seals as shown in Fig. 8 (Washington State DOT, 2005), have been used in new construction and in rehabilitation projects. Traditionally, such sealants are used on shorter spans where joint movement is up to 6 mm (0.25 in.). However, many new sealants have been developed and claimed by the manufactures for larger movements. The sealants with movement rating +100/-50% are not uncommon today.

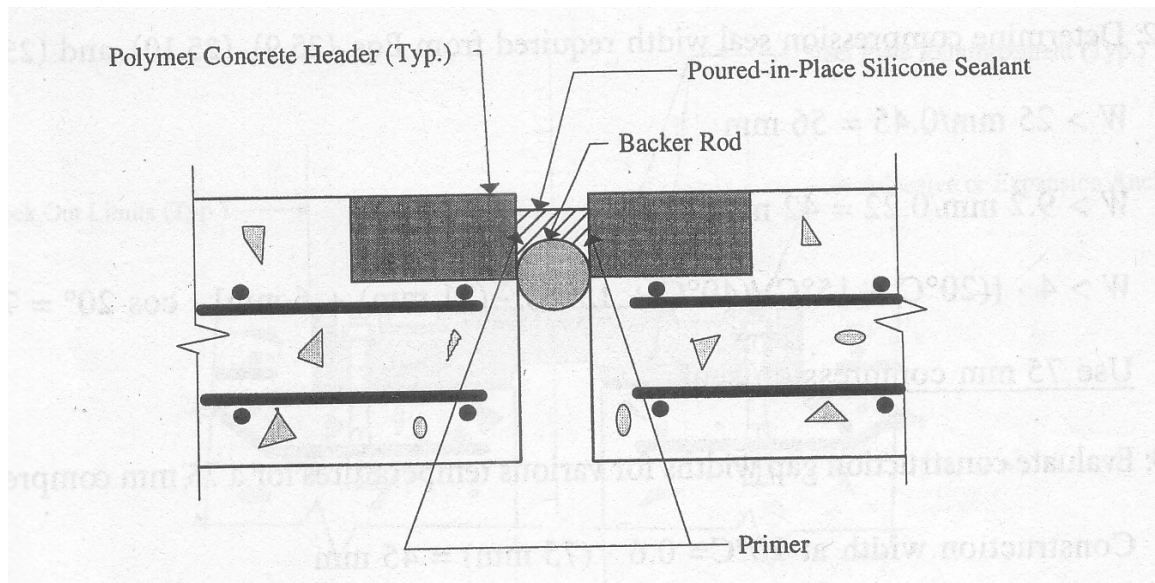


Figure 8. Polymer poured-in-place seal.

The system typically includes an elastomeric header with pourable silicone sealer and polyethylene backer rod as joint filler. The backer rod is squeezed into the joint to prevent the spilling of the sealant through the joint opening and to form the required sealant shape. The silicone is a self-leveling, rapid curing, one-part or two-part polymeric material. Most silicone sealants possess good elastic performance over a wide range of temperatures while demonstrating high levels of resistance to UV and ozone degradation. Rapid curing sealants

are ideal candidates for rehabilitation in situations where significant traffic disruption from extended traffic lane closure is unacceptable. The major problem associated with this type of system is debonding of the seal material from the joint face [Fig. 9 (Courtesy New Hampshire State DOT)]. Other problems including splitting and damage from non-compressible debris have also been reported.



Figure 9. Debonding of silicone sealant.

2.2.2 Medium Movement Joints

Strip seal and finger joints are most popular medium movement joints.

2.2.2.1 Strip Seal

A strip seal consists of “V” shape preformed neoprene gland mechanically locked into a metal facing on both sides of the joint. Movement is accommodated by unfolding of

the elastomeric gland. Movement capacity of strip seal is up to 100 mm (4 in.). A typical detail is shown in Fig. 10 (Washington State DOT, 2005).

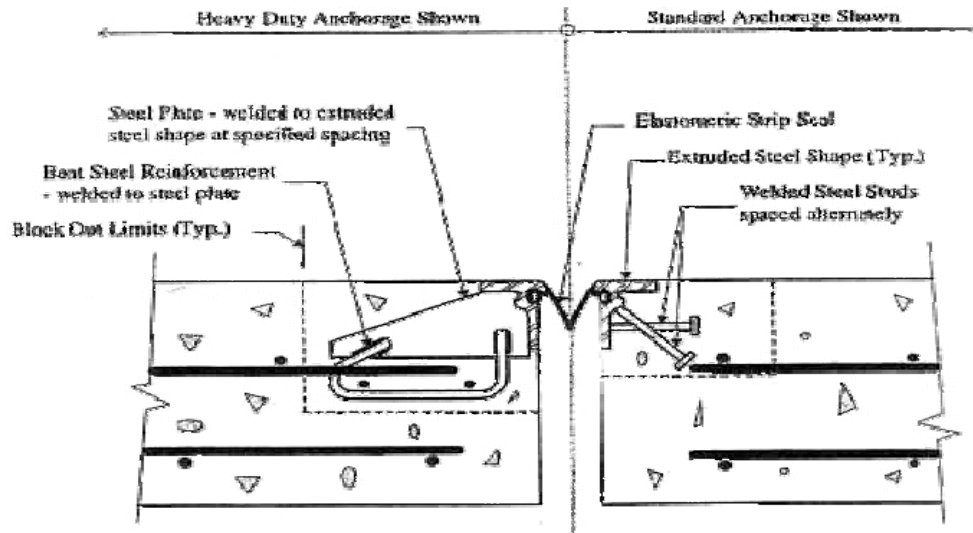


Figure 10. Strip seal.

Properly installed strip seal systems are watertight and have demonstrated relatively better performance. Another benefit is that damaged or worn glands can be replaced with minimal traffic disruptions. Many state agencies such as Minnesota, New Jersey, and Pennsylvania have reported better and more durable performance of strip seals with respect to other joint seals. The most prominent disadvantage of this system is that the elastomeric gland exhibits a proclivity for accumulating debris. Incompressible materials lodged in membrane crevices resist joint movement and results in premature gland failure [Fig. 11 (Ohio State DOT, 2003)]. Additionally, faulty installations or unclean locking devices cause gland pullout from metallic rail edges [Fig. 12 (Ohio State DOT, 2003)].

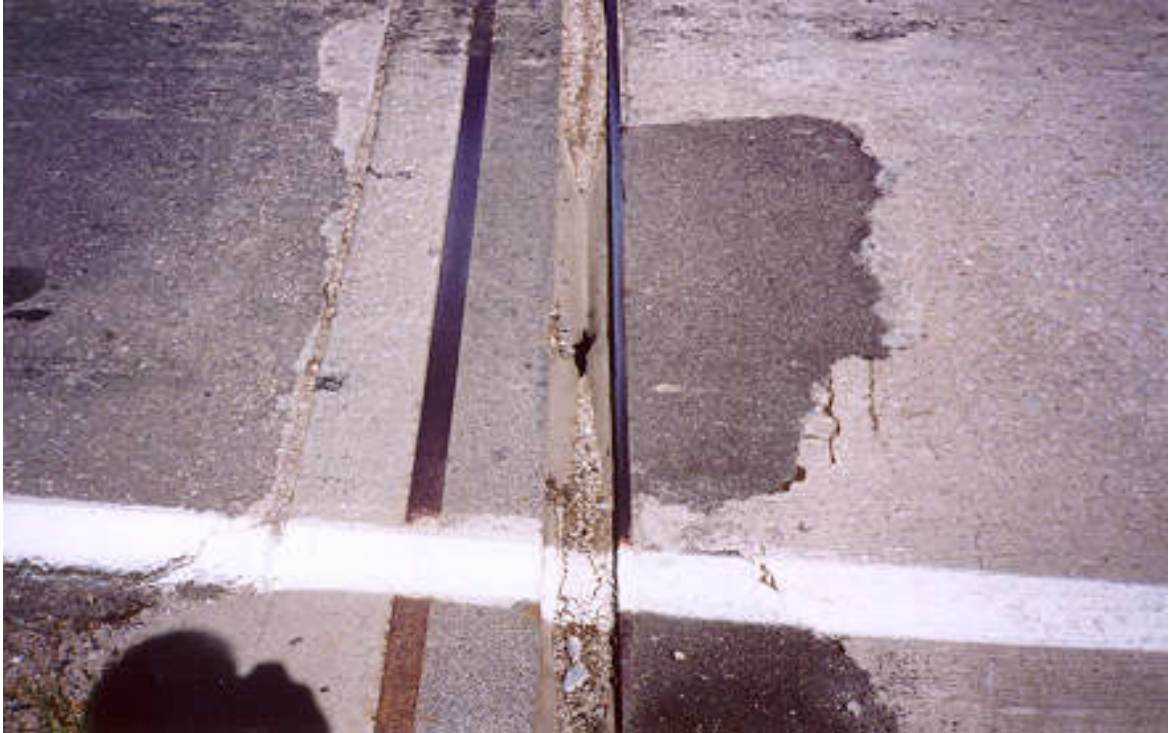


Figure 11. Tearing of seal due to incompressible debris.



Figure 12. Gland missing.

2.2.2.2 Finger Plate Joints

These joints are generally fabricated from steel plate and are installed in cantilever or prop cantilever configurations [Fig. 13 (Burke, 1989)]. The joints accommodate rotational movement in addition to differential vertical deflection across the joint. Generally, drainage trough is below the joint to intercept deck water and debris and carry it away from substructure members.

Agencies such as Arkansas and Maine have given high ratings for finger joints. However, open finger joints without drainage trough were no longer specified in Maine. Where narrow bicycle tires are anticipated, floor plates should be used in the shoulder area. On evaluation of bridge joints for Pennsylvania, Dahir and Mellott (1985) commented that cantilever fingers can be bent or broken under continuous pounding of heavy traffic. Also, due to rapid accumulation of cycles of fatigue loadings, welding details are critical for these systems.

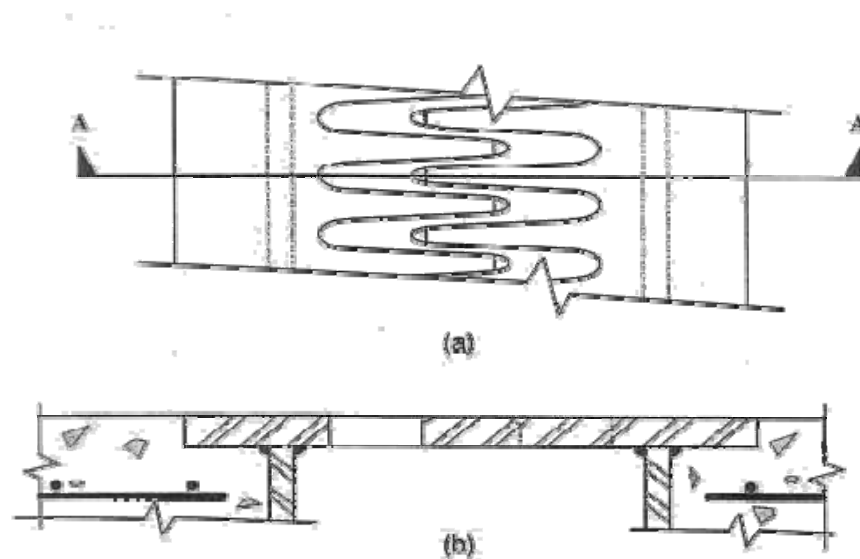


Figure 13. Finger Joint. (a) Plan view; (b) Section A-A.

2.2.3 Large Movement Joints

Large movement joints are used for accommodation movements greater than 100 mm (4 in.). Most common among them are plank seal and modular joint.

2.2.3.1 Plank Seal

The plank seal consists of monolithically molded elastomeric panels reinforced with steel plates as shown in Fig. 14 (Burke, 1989).

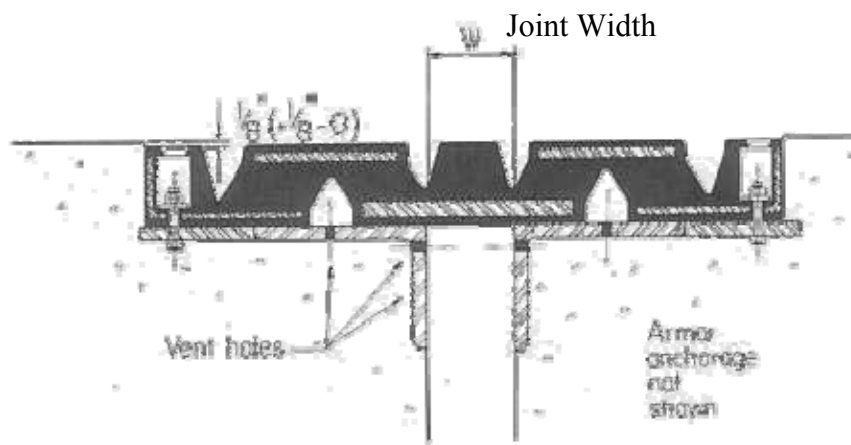


Figure 14. Plank seal

The plank seal is used for movement ranges from 50 to 330 mm (2 to 13 in.). These joints have lost favor among the agencies that use snowplows. Snowplows cut into the material and occasionally destroy complete sections. Cost is an important consideration with the system as complete replacement of the joint is required when damaged. Anchor failure is another problem. Bolts and nuts connecting panel to bridge decks are prone to loosening and breaking under high-speed traffic. Figure 15 (Purvis, 2003) shows an example of plank seal failure.

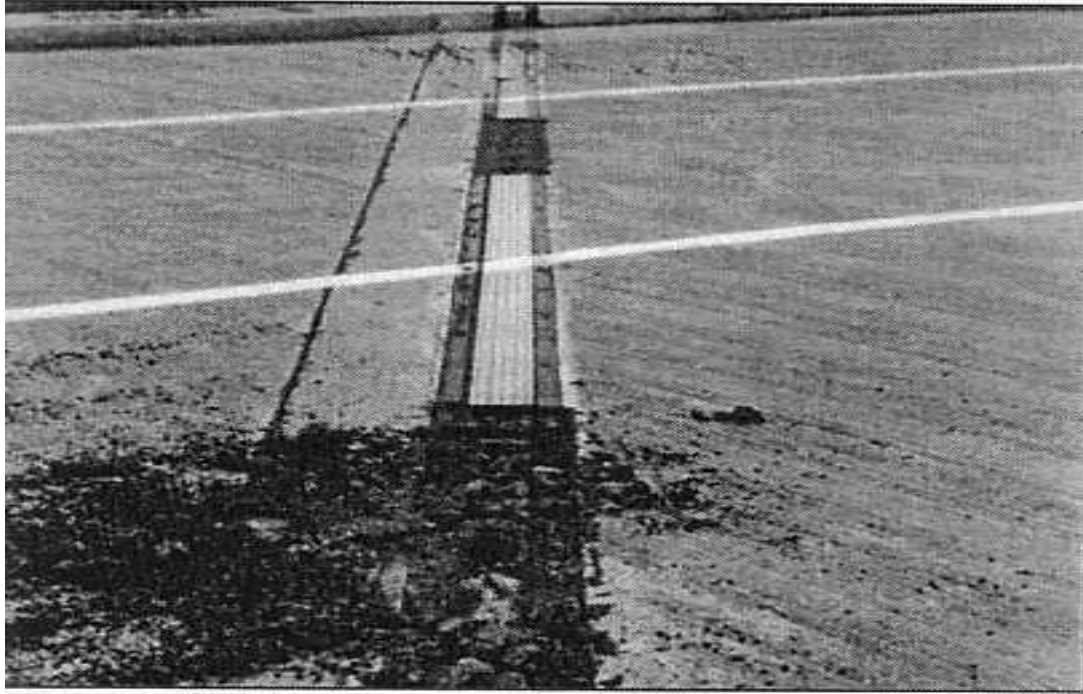


Figure 15. Damaged plank seal.

2.2.3.2 Modular Joints

Modular bridge expansion joints, shown in Fig. 16 (Connor, 1999), are complex, expensive structural systems designed to provide watertight wheel load transfer across wide expansion joint openings. The joint components are sized according to the magnitude of movement. Typical movements associated are 150 mm (6 in.) to 600 mm (24 in.). The system comprises of a series of center beams supported atop support bars. The center beams are oriented parallel to joint axle while support bars span parallel to movement direction.

Fatigue cracking of welds, damage to neoprene sealer material, and damage from snowplows are major problems with this type of system. An example is shown in Fig. 17 (Purvis, 2003). Most agencies are reluctant to use modular joint on account of their high initial costs and high maintenance cost.

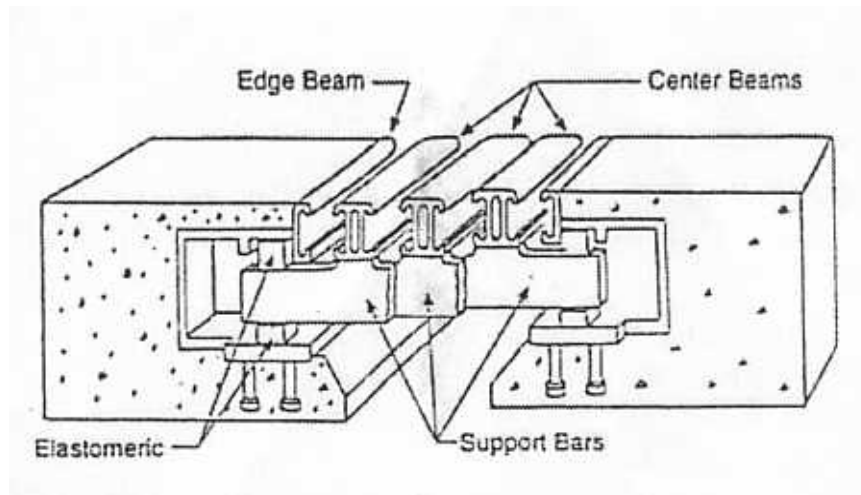


Figure 16. Modular joint.

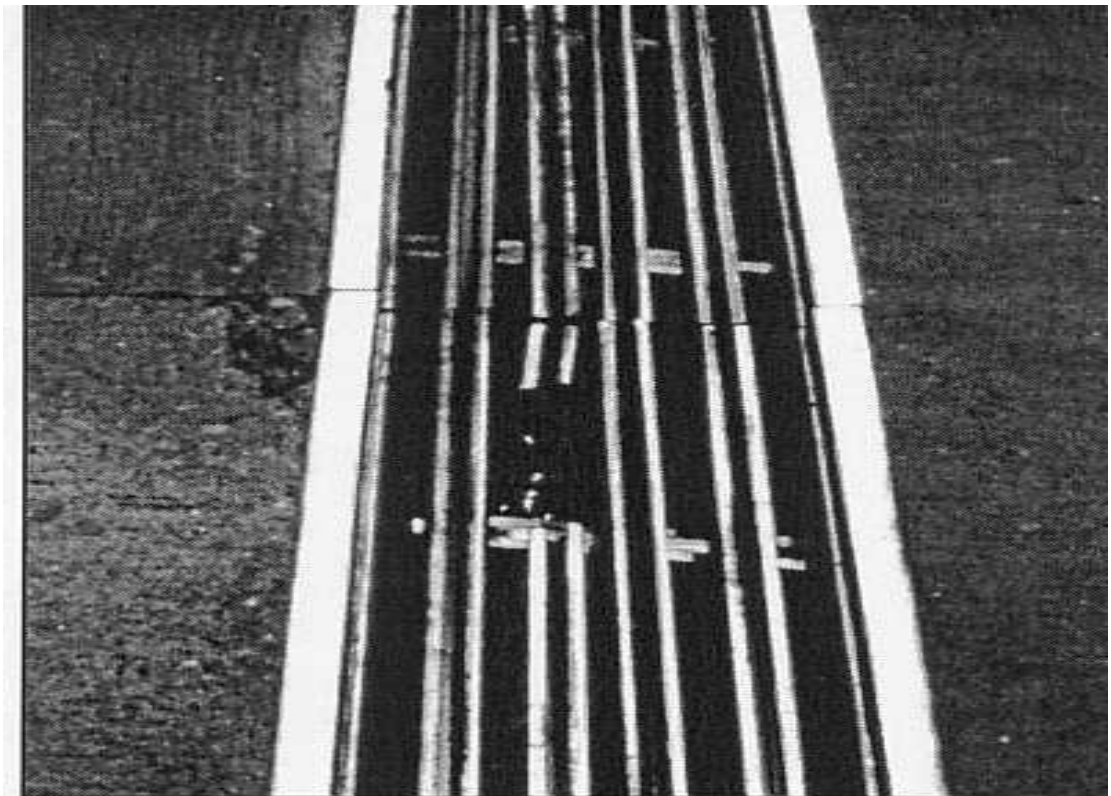


Figure 17. Damaged modular joint.

2.3 BRIDGE EXPANSION JOINTS IN NEW ENGLAND STATES

Transportation agencies in New England states were contacted and information on types of expansion joint systems they have in their state bridges, along with relative performance of each type of system, was collected. Based on their responses, the various types of joint systems currently in use in New England states and their range of applicability and performance are summarized in Table 1 below.

Table 1. Various Bridge Deck Joints in Practice in New England

State	Types of Joints Employed	Anticipated Movement Range (MR) or Deck Span Length (L)	Comments
Connecticut	a. <u>Asphaltic Plug Joint</u> b. Silicone Sealant c. Neoprene Strip Seal d. Modular and Finger Plate	MR < 40 mm MR: 40-80 mm MR: 80-100 mm MR > 100 mm	95 % of all joints Elastomeric header Elastomeric header -
Maine	a. <u>Compression Seal</u> b. Silicone -Pour-in-Place c. Gland Seal d. Evazote Seal e. Asphaltic Plug Joint	- Small MR MR > 100mm - MR < 50mm	Most preferred Rehabilitation project - Limited success No success, Failure in short period
Massachusetts	a. Saw Cut Seal b. Asphaltic Plug Joint c. Strip Seal d. Finger Joint	L < 15 m L > 20m, <35m L > 35 m Large spans	- Skew < 25° Armored Neoprene trough
New Hampshire	a. Silicone based Sealant b. Roadway Crack Sealer c. <u>Asphaltic Plug Joint</u> d. Finger Joint	Small MR For short spans and on fixed ends L: 80'-140' L: 140'-180'	Reasonable success Hot applied, petroleum based Good results, skew <25° -
Rhode Island	a. Compression Seal b. Strip Seal c. <u>Asphaltic Plug Joint</u> d. Open Joints, Sliding Plate Joint	- Large MR Short Spans (L<100') -	Poor performance, No more in use Poor performance, Leakage Most preferred Exist in old construction
Vermont	a. <u>Asphaltic Plug Joint</u> b. Vermont Joint c. Finger Plate Joint d. Modular Joints	MR: 50-75mm; Short Spans (L<90') MR < 75mm (L>90') MR > 75mm Very Large MR.	Most preferred - - Rarely used

From the data provided in Table 1, asphaltic plug joint seems to be the predominantly used expansion joint system in New England region. They are normally used to accommodate movement ranges of up to about 50 mm with a skew angle less than 25°.

2.4 EVALUATION OF PERFORMANCE OF EXPANSION JOINTS

2.4.1 Common Joint Defects

Since installation, joints are attacked not only by natural elements such as water, dust, dirt, ultraviolet rays, and ozone, but also elements introduced by humans such as deicing chemicals, snowplows, or traffic impacts. Each possible defect is a contributing factor to deterioration. The common joint defects are as follows (Guzaltan, 1993):

1. Loose, torn, split, cracked, damaged, or hardened seal;
2. Accumulation of debris and incompressible materials in the seals, drainage troughs, downspouts, and silting basins;
3. Loose, rusted, cracked, missing, or damaged steel plates, shapes, anchorage, bolts, nuts and other metal components;
4. Cracked and spalled concrete and rusted or exposed reinforcement steel or structural steel in deck joint substrate;
5. Water leakage and its impact on the underside of deck;
6. Impact of noise during passage of vehicles over joint;
7. Restriction of freedom of joint movement;
8. Impact of rotation, tilting, or settlement; and
9. Incorrect joint opening or improper joint clearance and alignment.

2.4.2 Factors Influencing Joint Performance

The performance in service of many joints has been variable, and the reasons for this are not readily apparent. A survey conducted by Transportation and Road Research Laboratory identified that a wide range of factors influence the performance of joints (Price, 1984). They include:

1. Structural movements at joint,
2. Traffic loading,
3. Joint Design,
4. Materials used,
5. Detritus, foreign matter, and corrosion,
6. Bond and anchorage,
7. Condition of substrate,
8. Weather and temperature during installation and service,
9. Detritus, debris, and corrosion,
10. Site preparation and workmanship,
11. Performance of bearings

These factors differ between and within joint types and frequently it is a complex combination of factors which affect serviceability and not necessarily the same combination or sequence for all the joints. Often the action of one factor instigates another. For example, traffic density and axle loading may influence the performance of bearings, and site preparation and workmanship could influence the quality of bond and anchorage, all of which influence the performance of joints.

2.4.3 Bridge Deck Joint Evaluation

A significant amount of literature is available on performance studies of bridge deck expansion joints and sealant systems [For example, see Biel and Lee (1997), Chang and Lee (2002), Eacker and Bennett (2000), NCHRP (1979)]. These studies usually involve either questionnaire survey to determine the level of success that transportation departments have experienced in the use of various types of bridge deck joints or the field inspection of joints at selected test sites. The most frequently encountered problems and their causes and the merits of joint types are identified from the survey which is used to rank the performance of these joints.

Figure 18 shows a sample of completed evaluation form used in bridge deck joint evaluation survey conducted by Transportation Research Board (Burke, 1989). Joint types included in survey were open joints, finger joints, slider joints, compression seals, strip seals, sheet seals, plank seals, cellular seal, and modular compression seals. Figure 19 shows the summary of the evaluations contained on the forms received from 31 transportation departments who participated in the survey. The summary shows the relative success or failure that has been experienced by transportation departments in the selection and application of various types of bridge deck joints.

Field performance of three types of joint sealants, namely silicone sealants, PVC-coal tar sealants, and hot-pour sealants were compared in a study performed for Utah Department of Transportation (Loza et al, 1987; Voigt and Yrjanson, 1992). The sealants were installed and their performances were evaluated after one, two, three, and eight years. After two years silicone materials were observed to be performing well (4% failure) and the sealant continues

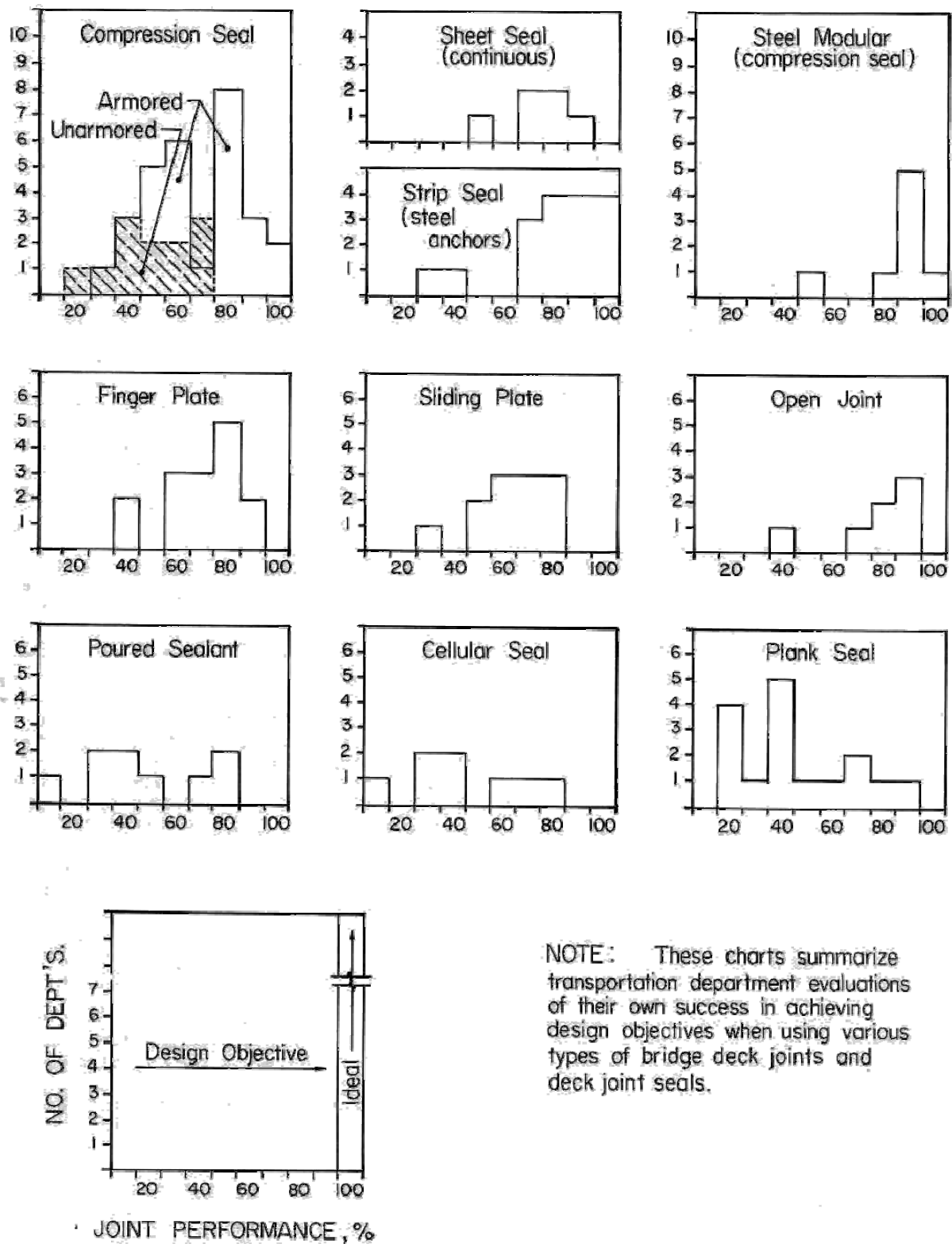
to perform well after eight years. The PVC-coal tar was having adhesion problems, and the hot-pour rubberized asphalt materials performing poorly having up to 80 % failure.

Sample Response

GENERALIZED BRIDGE [DECK JOINT] EVALUATION ①										
JOINT TYPE Attach a copy of a representative detail drawing or sketch of the joint design being rated. Please cross-reference.	RATING (0-10 scale) (for all joints of the type identified)			REASON (for adverse rating)						COMMENTS Please indicate the most specific flaw or faults which appear to be responsible for adverse ratings.
	PERFORMANCE ② Poor 0 2 4 6 8 Adequate 10	DURABILITY ③ Poor 0 2 4 6 8 Adequate 10	MAINTENANCE ④ Continuous 0 2 4 6 8 Moderate 10	Product Design	Joint Design	Fabrication	Construction	Maintenance	Joint Quality	
(A) Compression seals a with joint edge armor	0 2 4 6 8 10 [Rating: 10]	0 2 4 6 8 10 [Rating: 10]	0 2 4 6 8 10 [Rating: 10]	☐	☒	☐	☒	☐	☐	Leaks - poor curb geometry
() Armor Joint with a Compression Seal b	0 2 4 6 8 10 [Rating: 10]	0 2 4 6 8 10 [Rating: 10]	0 2 4 6 8 10 [Rating: 10]	☐	☐	☐	☐	☐	☐	
() Armor Joint with a Elastomeric Seal b	0 2 4 6 8 10 [Rating: 10]	0 2 4 6 8 10 [Rating: 10]	0 2 4 6 8 10 [Rating: 10]	☐	☐	☐	☐	☐	☐	
() Strip Seal a Steel Extrusion b Heavy Wall	0 2 4 6 8 10 [Rating: 10]	0 2 4 6 8 10 [Rating: 10]	0 2 4 6 8 10 [Rating: 10]	☐	☐	☐	☐	☐	☐	
() Modular Joints a Steel Systems b Alum Systems	0 2 4 6 8 10 [Rating: 10]	0 2 4 6 8 10 [Rating: 10]	0 2 4 6 8 10 [Rating: 10]	☐	☐	☐	☐	☐	☐	
() Elastomeric Joints a (Transfer and b Moba-flex)	0 2 4 6 8 10 [Rating: 10]	0 2 4 6 8 10 [Rating: 10]	0 2 4 6 8 10 [Rating: 10]	☒	☐	☐	☒	☒	☐	Shallow damage and noise problems. Shallow damage and anchor bolt loosening.

① For joints installed during the last 10-15 years ② Fulfills design objectives ③ Relative to all joints designs

Figure 18. Sample evaluation form.



NOTE: These charts summarize transportation department evaluations of their own success in achieving design objectives when using various types of bridge deck joints and deck joint seals.

Figure 19. Summary of transportation departments' evaluation of bridge deck joints.

A study conducted for Indiana Department of Transportation (Chang and Lee, 2002) investigated the performance of compression seal, strip seal, integral abutment, poured silicone, and polymer modified asphalt (PMA) joints. Besides the usual questionnaire survey, the study used the logistic regression approach to analyze the Indiana Department of Transportation (INDOT) roadway management data to evaluate the joint performance. The final joint performance ranking based on parameters such as age, traffic volume, and settlement, are shown in Table 2. Higher ranking indicates the slower deterioration rate under the influence of the factor. Due to the small number of data, poured silicone was not included in the analysis. Similarly, PMA joint could not be compared with other types of joints because no common factor was selected for the PMA joint.

The study indicated that the strip seal joint performed the best, compression seal second and integral abutment joints third, under the conditions of age and settlement. The strip seal joint performed better than the compression seal joint under the conditions of traffic loading.

Table 2. Joint Performance Ranking Based on Deterioration Rate

Ranking	Variable		
	Age	Traffic loading	Settlement
1	Strip seal	Strip seal	Strip seal
2	Compression seal	Compression seal	Compression seal
3	Integral abutment	-	Integral abutment

The evaluation study performed by Virginia Department of Transportation (VTDOT) that focused on joint sealing systems showed mixed results with regard to the performance of the generic systems evaluated (French and McKeel, 2003). The research procedure employed in this evaluation was a series of case studies of individual trials of joint sealing systems used

by VDOT during the past several years. It did not include butt, sliding plate, and finger joints. Larger modular joint systems were also excluded. Each system was found to perform successfully at one occasion, while showing a failed installation at other. The study concluded that adherence to recommended installation procedures is essential to attaining satisfactory service from a joint sealing system.

A study conducted by NCHRP (Purvis, 2003) showed that most of the closed joints start leaking water within a period of 5 years from the joint installation. This leakage was attributed to the following factors:

(a) Improper Installation, (b) Poor maintenance, (c) Puncture/damage by debris, (d) Defective product, (e) Damage by traffic, (f) Damage by snowplow, and (h) Temperature extremes.

Debris collection was found to be another problem with deck joints. Almost all of the agencies who took part in the study reported that their deck joints commonly collect debris, with 80 % noting that the debris had adverse effects on joint performance. The study listed following other performance problems for bridge deck expansion joints:

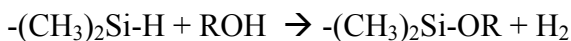
- Compression failure when joint closes,
- Snowplow damage,
- Substructure movement, and
- Poorly formed headers.

3. DEVELOPMENT OF NEW SEALANT MATERIAL

3.1 SELECTION OF JOINT SEALANT MATERIAL

After reviewing the existing literature on expansion joint sealants, silicone based polymeric material was selected as the potential new joint sealant. Silicone sealants for concrete are well-established as the Cadillac of sealant systems. As such, they have long life, flexibility under all temperature conditions, outstanding moisture resistance and reasonable UV resistance, which can be improved with additives, and outstanding adhesion to a wide variety of surfaces.

Silicone chemistry is extremely versatile, with both one- and two-part room-temperature-curing formulations available, as well as one or two part thermally curing varieties. However, there are some important drawbacks of silicone sealants. Cost is high, relative to rubber-modified asphalt or even polyurethanes. In addition, the strength of the elastomer is low, so resistance to damage by the penetration of pebbles is limited. One possible route to improving on these two properties is to switch to silicone foams [e.g., Stadelmann (2001), Vincent (1972)]. Foams can be made using two-part systems. The normal method of foaming employs a two-part formulation with one ingredient containing a hydrosilane and the other an alcohol. When mixed, the reaction proceeds as follows:



with the hydrogen gas forming the bubbles resulting in a closed-cell foam (Dubiel et al. 1983). The alkoxy silane group is then available for reaction with water on the surface of the concrete to form silanol, which then condenses to form a silicone elastomer coating on the concrete. The hydrosilane can also react with silanol groups to form hydrogen and extend

the length of the chain. As this sealant material expansion can be high, cracks can be filled with less material, which will lower cost and partially compensate for the generally higher cost of the hydrosilane-functionalized prepolymers. The foam structure can often localize the damage created by penetration, and its low stiffness will reduce the transfer of shear stress to the fragile concrete-polymer interface. Spot repairs should be quick and easy.

Following requirements were kept in mind while developing the new silicone foam sealant material in the laboratory:

- Movement capability: sealant should be able to accommodate total contraction and expansion movements up to 1.5 inches, combined with shear stress to simulate skewed bridges
- Elasticity: sealant should be able to return to its original size after released from elongation or compression
- Modulus: low resistance to load at low temperatures. The lower resistance at lower temperatures is achieved through more flexible material formulation and keeping lower glass transition temperature
- Adhesion: sealant should be able to adhere well to a variety of joint substrates, such as concrete and steel
- Cohesion: material should be strong enough to resist tearing from tensile stress
- Compatibility: chemical reaction of a sealant to material that it contacts
- Weatherability: able to resist deterioration when exposed to natural elements such as ultraviolet sun rays and ozone
- Applicability: able to be applied at ambient temperature

- Reparability: should facilitate easy removal of damaged section and replacement with a new section able to bond with the existing system

3.2 LABORATORY DEVELOPMENT OF SILICONE FOAM SEALANT

Silicone foam sealant was prepared in the laboratory by adding Baysilone U430 crosslinker (GE Bayer Silicones, 2003), deionized water, and platinum catalyst (Gelest Inc., 2003) to the mixture containing equal amount by weight of Wabo[®] Silicone seal grey and white components (Malla et al. 2005a, 2005b). The percentage weights of crosslinker, water, and catalyst used for the silicone foam sealant preparation were 2.3, 1.53, and 0.39 % respectively with respect to the total weight of Wabo[®] Silicone seal grey and white mixture. Figure 20 presents a schematic representation of the chemical reaction for the foam formulation. Si-H in Wabo[®] Silicone seal and cross linker reacts with water in presence of platinum catalyst to form silanol and hydrogen gas (H₂). Si-OH of silanol can react with another Si-OH or with the crosslinker to further polymerize. The released hydrogen –leads to foaming of the sealant. The foaming of the sealant results in significant rise in the sealant volume. Preparation of foam test specimens showed 70% increase in the sealant volume after the chemical reaction. This is highly desirable feature as it will lead to the considerable saving in the sealant material during joint sealing operation and will force the sealant into areas with poor access. The volume rise was determined by preparing two types of sealant specimens: solid sealant specimen containing Wabo[®] Silicone seal grey and white components only, and foam sealant specimen containing crosslinker, water, and platinum catalyst in addition to the solid sealant grey and white components. The volume occupied by these two sealant types were measured on complete of cure reaction and rise was calculated.

elastomers to behave elastically, as the name implies, such that they are capable of recovering from large deformations.

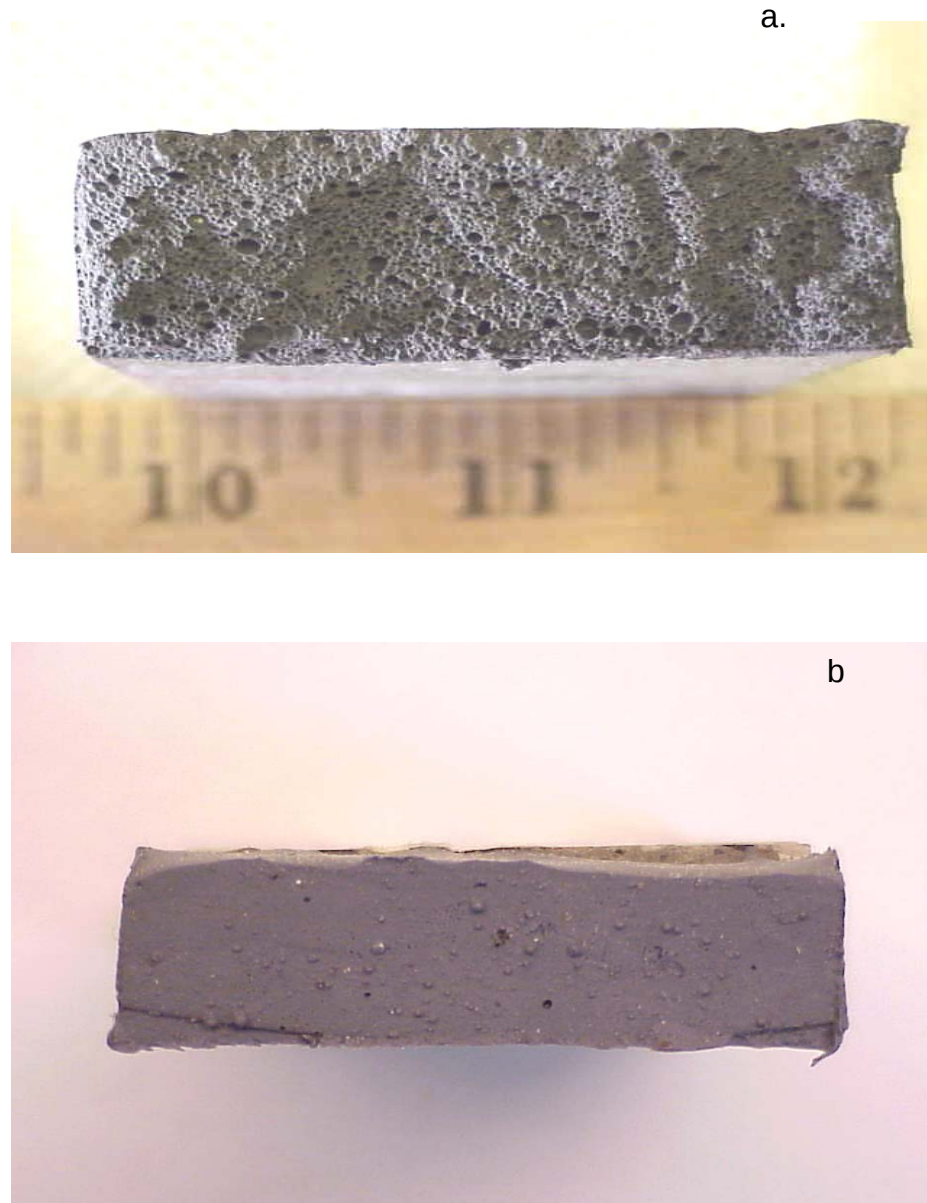


Figure 21. Two silicone seal materials
(a) Silicone foam sealant, (b) solid sealant.

4. LABORATORY EVALUATION TEST METHODOLOGY

To determine the characteristics and evaluate the performance of the newly developed foam sealant, several important laboratory tests were proposed to be conducted. They included: tension, compression, shear, bonding, salt water immersion, temperature sensitivity, compression recovery, creep, stress relaxation, cure rate, tack time, and water tightness test. Some of the abovementioned tests were repeated on weathered sealant after its exposure to outdoor condition for 6 months. Similar tests were also proposed to be performed on a currently available commercial solid sealant (Wabo[®] Silicone Seal, Watson Bowman Acme Corp. 2003) intended to be used as a control during laboratory validation testing of the foam sealant. Preparation of test specimens and laboratory test methods are presented in this chapter.

4.1 TENSION TEST

4.1.1 Loading Test

Figure 21 shows the typical tension test specimen configuration. The test specimen consisted of two concrete blocks with a gap in between them that was filled with sealant. Dimensions of each concrete block were: depth, $D = 12.7 \text{ mm}$ (0.5 in.); width, $W = 50.8 \text{ mm}$ (2 in.); length, $L = 76.2 \text{ mm}$ (3 in.). The dimensions of the sealant gap were: depth, $D = 12.7 \text{ mm}$ (0.5 in.); width, $W = 50.8 \text{ mm}$ (2 in.); length, $l = 12.7 \text{ mm}$ (0.5 in.). Three such test specimens were prepared for each sealant type (foam sealant and solid sealant) to be tested. The foam sealant was prepared by the procedure described in the preceding section and poured into the gap formed between the concrete blocks. The concrete substrates were wiped

with a clean, dry, lint-free cloth prior to pouring of the sealant; however, the joint faces were not primed. Solid sealant specimens were prepared by hand mixing equal parts by weight of Wabo® Silicone seal grey and white components and then pouring the mixture into the gap between the blocks. Table 3 shows the different material components and the amounts used to prepare a tension test specimen. Whenever necessary, the sealant surface was tooled to ensure complete filling and contact with substrate surfaces. The test specimens were cured for 21 days at $23 \pm 2^\circ\text{C}$ (room temperature). The relative humidity, however, was not monitored and maintained. To simulate actual field conditions, no elevated-temperature post cure was used.

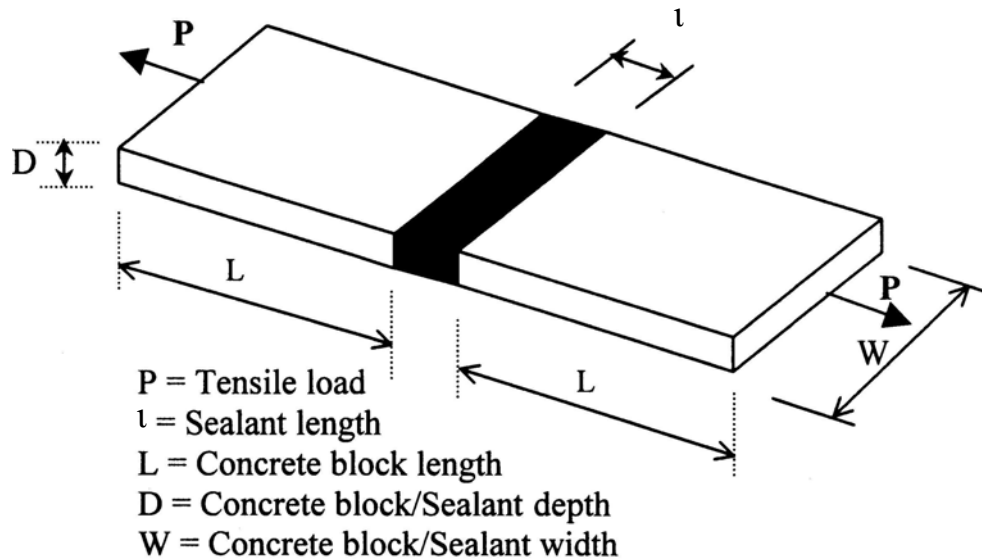


Figure 22. Tension test specimen.

Table 3. Sealant Components for Tension Test Specimen

Components	Foam sealant (gram)	Solid sealant (gram)
Wabo grey	3.50	6.50
Wabo white	3.50	6.50
Baysilone	0.1615	None
U430 crosslinker	0.107	None
Water	0.107	None
Pt-divinyltetramethyl- disiloxane complex (catalyst)	0.027	None

An Instron tensile tester (Model 1011) (Fig. 23) was used for testing the specimens prepared above. The machine was capable of producing uniform rates of grip separation varying from 1 mm/min to 500 mm/min. The load cell was connected to a computer for recording the applied force. The crosshead movement was used to calculate the elongation. The test specimen was placed in the grips of the testing machine, using care to adjust the specimen symmetrically to distribute tension uniformly over the sealant cross section. Due to the low aspect ratio of the specimens, the state of stress is not simple extensional, but because of the high compliance of the material, this was judged to have minimal effect on the results. The specimens were then pulled at a constant crosshead velocity of 10 mm/min (nominal strain rate of 0.013 s^{-1}) until the failure occurred (Fig. 24). Failure here refers to either tearing apart of the sealant material (Cohesive failure) or detachment of the seal from the concrete block substrate (Adhesive failure). The nominal stress and strain developed in the sealant material were calculated using the following mathematical expressions (Eq.3 and Eq. 4).

$$\sigma = \frac{P}{A} \quad \text{----- (3);} \quad \varepsilon = \frac{\Delta}{l} \times 100 \% \quad \text{----- (4)}$$

Where, σ = Average normal stress (nominal); P = Applied tensile force; A = Unstrained sealant cross sectional area; ϵ = Normal strain (nominal); Δ = Sealant extension; and l_0 = Unstrained sealant length

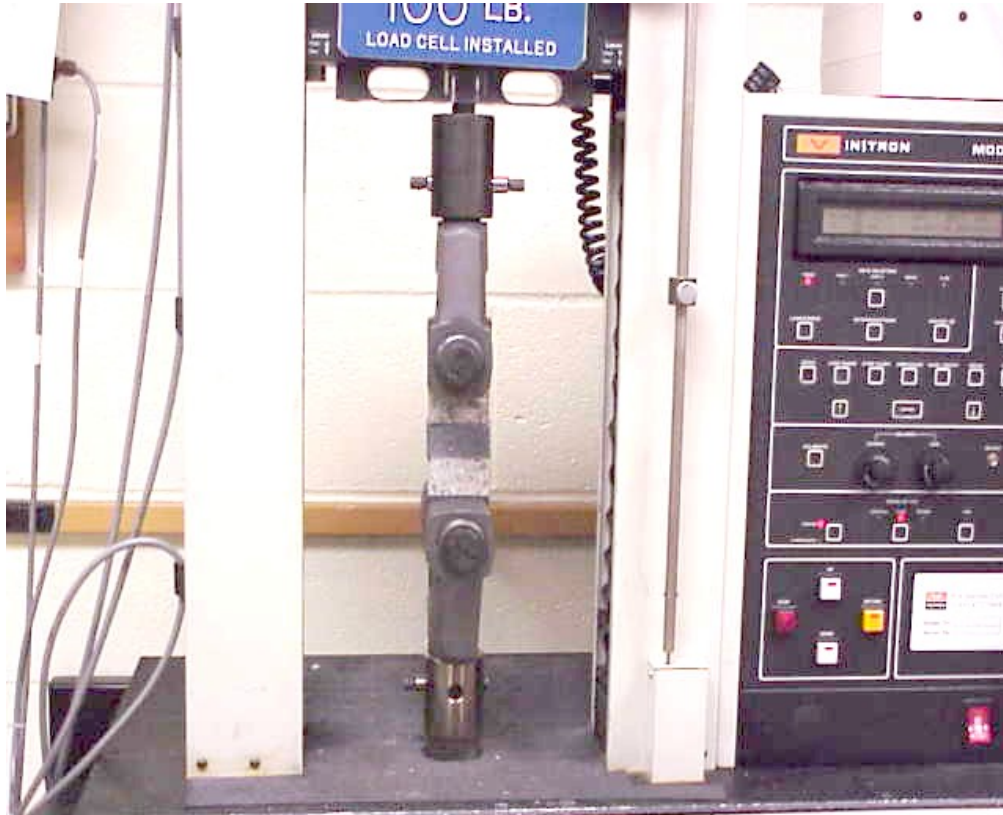


Figure 23. Instron testing machine (Model 1011) with tension specimen.

4.1.2 Loading and Unloading Test

The loading and unloading behavior of sealants in simple tension was also studied. The tension test specimens were loaded in the Instron machine up to the elongation of 300 % strain at the rate of 10 mm/min, and then unloaded at the same rate until they reached their original length (Zero strain). The procedure was repeated for five consecutive cycles of loading and unloading.

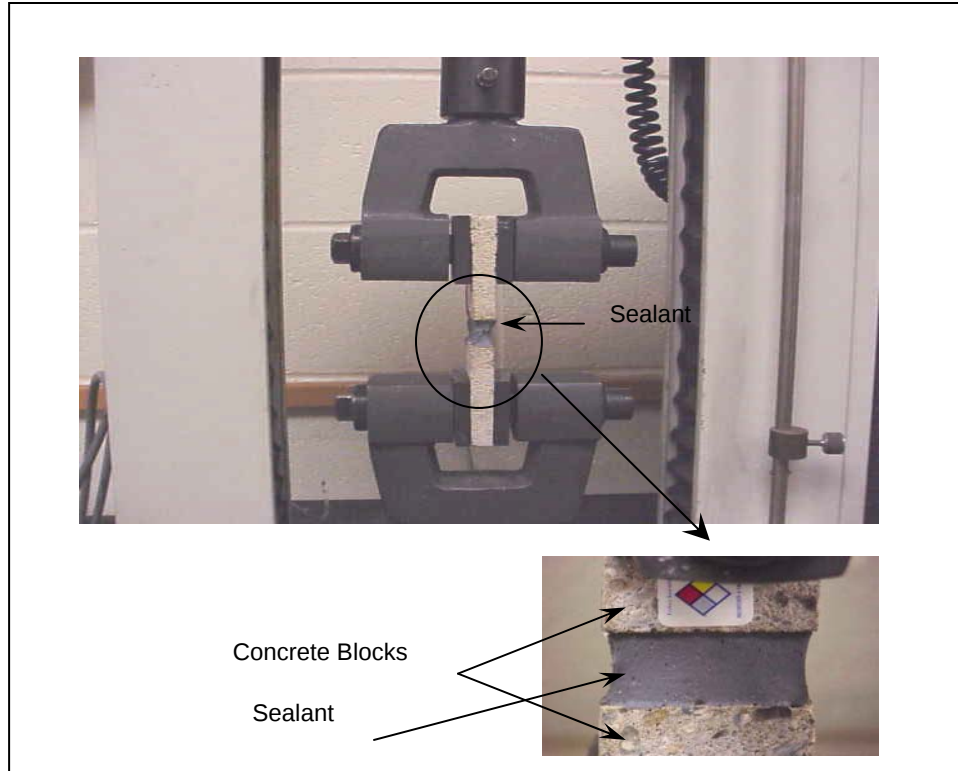


Figure 24. Tension test of sealant using Instron machine.

4.2 COMPRESSION TEST

4.2.1 Loading Test

A sealant block 76.2 mm (3 in.) by 25.4 mm (1 in.) by 12.7 mm (0.5 in.) was cast and cured at standard laboratory conditions ($23 \pm 2^\circ \text{C}$) for 7 days. After curing, test coupons were cut from the sealant to produce 3 uniform test samples each of size 25.4 mm (1 in.) by 25.4 mm (1 in.) by 12.7 mm (0.5 in.). Three such test samples were prepared for each type of sealants (foam sealant and solid sealant). The upper and the lower grips of the Instron testing machine were replaced with a cylindrical loading head and a circular bearing plate, respectively. Test specimen was carefully placed on the bearing plate so as to align its axis with the center of thrust of the cylindrical loading head. All specimens were uniaxially

compressed at a uniform strain rate of 10 mm /min to the half of their thickness (50% strain) and the modulus at this strain was obtained. A schematic diagram of the test set up is presented in Fig. 25.

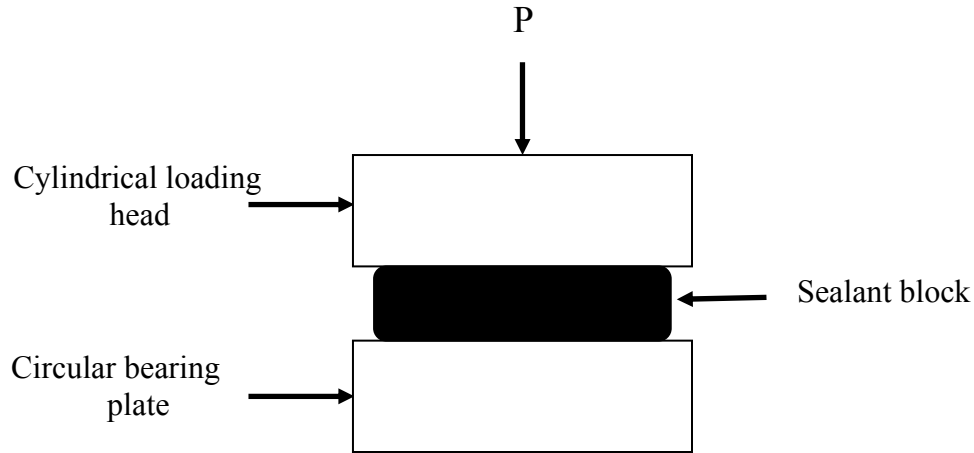


Figure 25. Compression of sealant.

4.2.2 Loading and Unloading Test

As in the tension test, sealant behavior under compression loading and unloading cycles was also evaluated. The specimens were compressed using the Instron machine to half of their original thickness (50 % strain) at the rate of 10 mm/min, after which the load was released by reversing the motion of the loading head at the same rate till the strains in the specimens were 0%. The procedure was repeated for 5 consecutive cycles of loading and unloading during which force values were constantly measured.

4.3 SHEAR TEST

Figure 26 shows shear test specimen in double lap joint configuration (sandwich arrangement) used in this study. As shown, the middle moving block shears two sealant slabs

between two fixed blocks. The sealant layer dimensions on each joint were as follows: thickness, $t = 6.3 \text{ mm}$ (0.25 in.); height, $h = 25.4 \text{ mm}$ (1 in.); width, $b = 50.8 \text{ mm}$ (2 in.) (Direction out of paper). This gives sealant-substrate contact area on each side equal to 1290 mm^2 (2 in.²). The inset in Fig. 26 shows the free-body diagram of the deformed sealant under the applied load P . Three test specimens for each sealant type were prepared and cured for 14 days at $23 \pm 2^\circ\text{C}$. Cement mortar substrates were used in contact with the sealant surface.

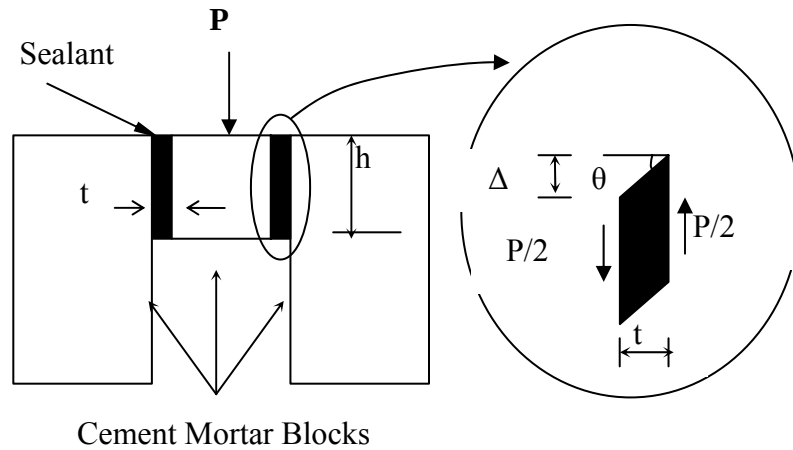


Figure 26. Shear test specimen.

Instron testing equipment described in section 5.1 was used for the shear test. As shown in Fig. 27, the upper lower grip was removed and the shear sandwich was placed symmetrically below the movable loading head. The center block was pushed downward 25 mm/min (strain rate of 0.066 s^{-1}) until the sample failed. The shear stress (τ), shear strain (γ), and elastic shear modulus (G) of the sealant were determined using the following relationships (Eq. 5, Eq. 6, and Eq. 7).

$$\tau = \frac{P}{2A} \text{ ----- (5);} \quad \gamma = (\tan \theta) = \frac{\Delta}{t} \text{ ----- (6);} \quad G = \frac{\tau}{\gamma} \text{ -----(7)}$$

Where, P = Applied Load; A = Sealant cross sectional area in contact with each substrate;

Δ = Vertical deformation; t = Sealant thickness; θ = Shear angle

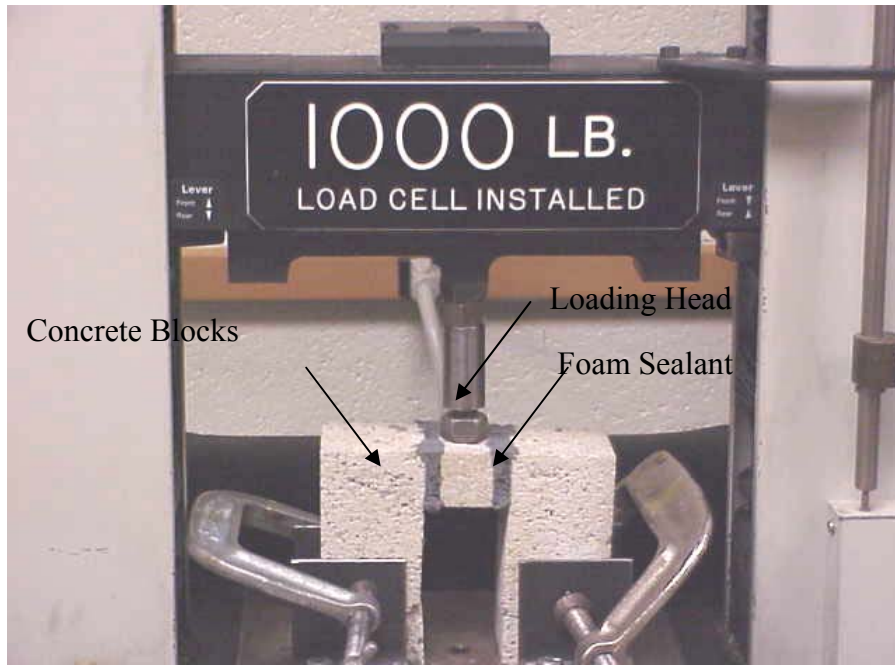


Figure 27. Shear test of foam sealant using Instron machine.

4.4 SALT WATER IMMERSION TEST

Sealants were exposed to saturated solution of sodium chloride (common salt) in water at an elevated temperature of 45 °C for 2 weeks to determine the influence on their adhesion and moisture resistance properties. The elevated temperature of 45 °C was maintained to facilitate the accelerated weathering and chemical effects. The primary effects due to moisture may include the absorption of water by the sealant and the diffusion of liquid

water to the sealant substrate interface. The absorption of water may cause either softening or enhanced cure of the sealant, whereas the diffusion may result in the impairment of the adhesive bond of the sealant to the joint surface (Beech, 1988) and damage during freeze-thaw cycles. The effects due to water absorption can be evaluated by means of tension testing in which the modulus and extensibility of sealants after immersion are measured as indices of performance (Beech and Mansfield, 1990). Effects on bonding due to immersion can be evaluated from the failure modes observed during the tests.

Three specimens of each type of sealants, foam and solid sealant were prepared using concrete substrates as described in tension test. After a week's cure at room temperature, all specimens were immersed in salt water at an elevated temperature of 45°C. After two weeks immersion, the specimens were taken out, allowed to dry in air for 3 to 4 hours, and then pulled to the rupture using the steady cross head velocity of 10 mm/min.

4.5 BOND (OVEN AGED) TEST

Adhesion to the substrate is a critical property of joint sealant. The test procedure as suggested by ASTM D 5893-96 specification (ASTM, 1997) was employed to evaluate the bond between the sealant and the concrete substrate. Oven aged samples were subjected to alternate cycles of cold extension and self-recompression and then inspected for any cracks and separations within the sealant or at the sealant-substrate interface. Specimens for this test were prepared in the same way as the tension test specimens. Three test samples of each type of sealants (foam sealant and solid sealant) were prepared and cured at standard laboratory conditions ($23 \pm 2^\circ \text{C}$) for 7 days, which was followed by oven aging of the samples at 70 °C for a week. The oven-aged samples were then put in a cold chamber maintained at -29°C for

4 hours before mounting them to the grips of Instron testing machine. The maximum and minimum temperature values have been chosen as the test temperatures as they are close to the expected upper and lower service temperature of most bridge joint systems in the U.S.A. The samples were extended at uniform rate of 6 mm/min to the length twice their original length (100 % strain), and then removed from the testing equipment and allowed to regain their original length at room temperature for 2 hours. The self-recompressed samples were again put in a cold chamber at -29°C and whole procedure was repeated for 5 cycles of extension and self-recompression. After the 5th extension, the test specimens were removed from the extension machine and immediately examined for obvious separation within the sealant and between the sealant and the blocks.

In addition to the visual evaluation of bonding at the sealant joint interface, the rate of loss of modulus with deformation cycles was also analyzed. To compare more realistically the modulus loss rates of two sealants with deformation cycles, a classical expression proposed by Chasset and Thirion (Thirion and Chasset, 1967) was used. The original Chasset-Thirion (C-T) equation was applied to stress relaxation of crosslinked elastomers and was explained in terms of the disentanglement of network chains that were attached at only one end to the network. The simplified expression (Eq. 8) used to calculate modulus after any number of cycles was:

$$E = E_{\infty} [1 + (a/n)^m] \quad \text{----- (8)}$$

Where E_{∞} is the modulus after infinite number of cycles, n , and a represents the number of cycles that will result in a modulus of 2 E_{∞} .

4.6 STRESS RELAXATION TEST

When an elastomer is subjected to constant strain under tension, compression or shear, the stored energy in the material decreases over time. This stress relaxation phenomenon occurs in elastomeric material due to two distinct effects, the first physical (due to viscoelasticity) and the second chemical (due to aging of the rubber such as by bond exchange or chain scission). At short times and low temperatures, physical effects are dominant whereas chemical effects are more apparent at longer times and higher temperatures (Smith, 1993).

Joint sealants operate both in tension and compression and hence stress relaxation measurements in tension as well as compression were used to measure sealing efficiency. To measure decay of sealant stress with time in tension, the tension specimen was pulled in an Instron machine to 100% strain and maintained at this stretched condition for a 24-h period. To determine the sealant relaxation behavior in compression, sealant samples were maintained at 50% compression strain using the Instron machine for a 24-h period. In both cases, the decrease in stress with time was monitored and recorded during test period. The stress measurements can be normalized to the initial stress measurement and expressed as percentage using the expression (Eq. 9):

$$R_t = (\sigma_0 - \sigma_t) / \sigma_0 \times 100 \quad \text{-----} \quad (9)$$

Where R_t is the stress relaxation after time t , σ_0 is initial stress, and σ_t is stress at time t .

The relaxation phenomena in the sealants were found to follow a Kohlrausch-Williams-Watts stretched exponential function (KWW equation). The original KWW equation was used to describe the dispersive relaxation phenomena observed by Kohlrausch

in a study of the loss of charge in Leyden jars (Kohlrausch, 1863). Williams and Watts (1970) described dielectric relaxation in polymers as being a stretched-exponential function. The stretched exponential form of the relaxation modulus $E(t)$ used to reduce experimental data (Eq. 10) was:

$$E(t) = (E_0 - E_\infty) \exp[-(t/\tau)^\beta] + E_\infty \quad \text{-----}(10)$$

Here $0 < \beta < 1$, t is time, and E_0 and E_∞ are constants. The parameters representing relaxation time (τ) and stretched exponential constant (β) depend on the material and can be a function of external variable such as temperature (Klafter and Shlesinger, 1986). These parameters were calculated according to the Eq. 10 using SigmaPlot 9.0 graphing software.

4.7 CREEP TEST

Creep is the increase in deformation after a specified time interval under a constant load and expressed as a percentage of the test piece deformation at the commencement of that time interval (Smith, 1993). Hence,

$$\text{Creep \% } (\epsilon_{\text{creep}}) = (D_t - D_I) / D_I \times 100 \quad \text{-----} (11)$$

Where, D_t = Deformation of the test piece after t minutes and D_I = Instantaneous deformation of the test piece.

As in stress relaxation, creep may be due to physical (at low temperature and short times) and chemical (at high temperature or long times) effects. Tensile test specimens were subjected to constant load and change in deformation with time were noted for 24-h period. Magnitudes of constant load for foam and solid were 11N and 30N respectively. These

values were chosen so as to cause sealants to undergo instantaneous elongation of approximately 100% upon the application of load.

4. 8 COMPRESSION RECOVERY TEST

During hot weather, an increase in temperature causes bridge deck slabs to expand. As a result, the joint starts to close and the sealant gets compressed. Sealants in bridge joints are typically expected to accommodate compressive movements of up to 50% of joint width. During prolonged compressed state, the stresses within the sealant may get relaxed which can make the sealant lose its ability to return to its original size and shape later when joint widens due to temperature decrease. This may cause the sealant to fail cohesively or/and adhesively due to higher tensile stresses developed as the joint opens. The scope of this test is to measure the sealant's ability to recover its original state after being subjected to compression under high temperature for a 24-h period. The test method suggested by ISO 815 (ISO, 1991) was used to determine the compression set at elevated temperature with only exception being the geometry of the test specimen. The test specimen consisted of a block of the sealant with 25.4 mm by 25.4 mm square cross section and 12.7 mm thickness which was placed between 2 parallel 50.4 mm by 50.4 mm faces of similar concrete blocks. The specimen was then compressed to 50% of the original thickness and placed in an oven holding it in compression at an elevated temperature of 45° C for 24 h. At the end of test period, the test piece was released from compression and its thickness was measured at different time intervals until the measured thickness reached more or less a constant value. The compression set ($\mathcal{E}_{set}$) is the difference between the original thickness of the test piece

and that after recovery, as shown in Fig. 28, expressed as a percentage of initially applied compression (Eq. 12).

$$\text{Compression set}\% (\epsilon_{\text{set}}) = (t_0 - t_r) / (t_0 - t_s) \times 100 \quad \text{----- (12)}$$

Where, t_0 = original thickness of the test piece, t_r = thickness of test piece after recovery, and t_s = thickness of test piece after initial compression

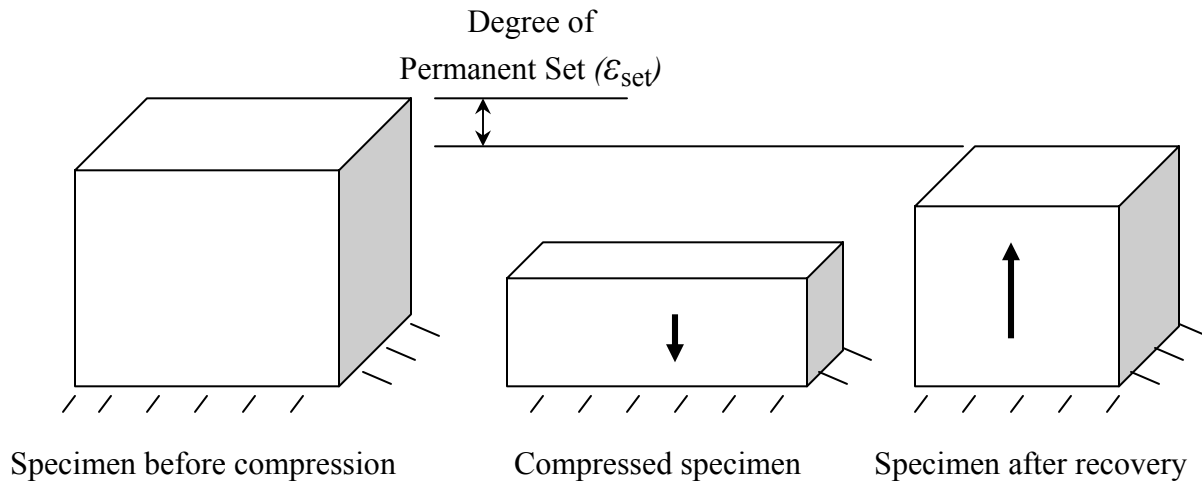


Figure 28. Diagram illustrating compression set.

4.9 TEMPERATURE SENSITIVITY TEST

4.9.1 High and Low Temperature Effects

Silicone sealants exhibit excellent thermal stability (Stoegbauer and Wolf, 1990). Resistances of up to 200 °C and, for special formulations, even 250 °C are quoted in the relevant literature. Cold-period loading of a seal is generally recognized as the most critical loading period because of possible sealant hardening at low temperatures. Below the glass transition temperature (temperature below which a polymer will lose elastomeric properties

and becomes hard and brittle like glass), sealants perform inadequately due to the stiffening of the material and failure stresses may reach in the seal or at the adhesive interface as the joint widens (Ketcham, 1995). Therefore, it was considered necessary to investigate the effects of maximum and minimum service temperature exposure on sealant performance.

Tension test specimens were used for this test. Two sets of sealant samples, each containing 3 foam sealant and 3 solid sealant specimens, were prepared. After a 2-week cure at room temperature, one set of samples was exposed to uniform high temperature of 70° C and another set was subjected to uniform low temperature of -36° C conditioning for a week period. These samples were then subjected to tension tests and the changes in its extensibility, stiffness and bonding characteristics were recorded.

4.9.2 Freeze and Thaw Cycle Test

Two sets of sealant samples, one containing 3 foam and another containing 3 solid tension test specimens, were prepared. After a 2-week cure at room temperature, both set of samples were subjected to alternate cycles of low temperature (-29°C) and room temperature (+24°C) conditions for a week period. Finally, all specimens were pulled to the failure in Instron machine at a uniform crosshead speed of 10mm/min. The modulus and extensibility of sealants were then compared with those obtained from tension test.

4.10 CURE RATE TEST

Sealant should cure fast enough to accommodate typical daily thermal movements and differential joint movement caused by traffic without being damaged. Development of sufficient integrity and strength in small time period is essential in maintenance work, such

as bridge joint resealing, to minimize traffic disruption. Tension test specimens were used to determine the cure rate of each sealant.

The test procedure involved repeated elongation of sealant specimens to 100 % strain at different time intervals and recording the corresponding stress values. For the first 24 h after the specimens' preparation, the test was performed at 3, 6, 18, and 24 h, after which the test was repeated at every 24 h period for 42 days.

4.11 TACK FREE TIME TEST

Tack free time is important in characterizing sealant as it is a measure of the surface cure time and sealant's resistance to dirt pick-up and impinging rainfall. It is the time required for the sealant surface to be non-sticky and usually determined by visual observation. Here, it should be understood that sealant cure reaction continues at molecular level for much longer time after being visibly completed and therefore, sealants may not have developed sufficient structural integrity to sustain large deformations after the specified tack time. For joint sealants, tack free time is desired to be as small as possible such as to cause minimal disruption to the road traffic. ASTM C 679 Test for tack free time was used in the laboratory. The test involved lightly touching a surface of a curing sealant with a polyethylene film at the regular intervals until sealant did not attach itself to the film.

4.12 WATER TIGHTNESS TEST

One of the critical requirements for the successful performance of any joint sealant is that it provides an effective barrier preventing water from passing through the joint on to the substructure elements below. The simple laboratory test to check watertight integrity of

sealant consisted of a hollow glass cylinder of 38.1 mm (1.5 in.) diameter and 63.5 mm (2.5 in.) height. The sealant was poured in the cylinder such as to form a sealant ring of 12.7 mm (0.5 in.) thickness at one end of cylinder which bonded well with the inner surface of the cylinder. A column of water, 38.1 mm (1.5 in.) high, was allowed to pond above the sealant for a period of 96 h and observation was made for any water leakage.

4.13 TESTS ON WEATHERED SEALANT

Deterioration in physical properties can occur when the elastomeric joint sealants are exposed to the weather effects (rain, snow, wind, and sunlight). This deterioration can be observed as cracking, peeling, chalking, color changes, and other surface defects, and ultimately by failure of the material. Presence of ozone, sunlight, oxygen, moisture, and temperature are the cause of deterioration. UV light present in sun radiation can cause surface hardening which can lead to crazing, chalking, and gradual erosion of the surface of the elastomer. Oxygen can cause oxidation of the polymer and leads to the loss of mechanical properties and elasticity and this effect is accelerated at high temperatures. Oxygen contained in dew can also cause internal oxidation.

Three tension test specimens and two shear test specimens of each sealant type (foam and solid) were prepared. Sealant specimens were exposed to outdoor condition in Connecticut beginning immediately after their preparation in laboratory for a period of nearly six and one-half months starting from the 14th of December, 2004 to the 28th of June, 2005. The intent was to subject sealants to environmental effects during both cold and hot weather seasons. Such outdoor exposure is expected to simulate the real field conditions for a bridge joint sealant with the absence of vehicular effects being the only major exception. One of the

bases for evaluation was the change in the appearance due to surface degradation, dirt pickup, and mildew. Besides, a variety of tests including tension, shear, stress relaxation, and loading and unloading were performed on the weathered sealant samples to determine outdoor exposure effects on their properties.

5. LABORATORY TEST RESULTS AND DISCUSSION

Results from a wide variety of laboratory tests outlined in chapter 5 are presented and discussed below.

5.1 TENSION TEST RESULTS

5.1.1 Loading Test Results

The following properties were evaluated from the tensile test: ultimate tensile strength (kPa), ultimate elongation (%), modulus (stress) at 100 % strain, loading-unloading behavior, and failure mode (adhesive/cohesive). Ultimate values refer to the values at the point of maximum load where failure initiated. The nominal or engineering stress and strain were calculated considering the original unstrained cross sectional area (12.7 mm x 50.8 mm) and original unstrained length (12.7 mm) of the sealant. Strictly, the stress should be the force per unit area of the actual deformed section (true stress) but this is rather more difficult to calculate. The modulus at 100 % strain was taken as the stress to extend a standard specimen by the amount same as its original length. This is due to the fact that a stress/strain curve for rubber does not contain linear elastic portion as is usual with, for example, metals, and hence, modulus is not measured as such but quoted as the stress at some percentage elongation.

Figure 29 shows typical stress-strain behavior of the two sealant types (foam sealant and solid sealant). It can be seen that stress–strain dependencies are not linear in nature, and therefore, Hooke’s law, in general, is inapplicable. Stress-strain curves also illustrate low resistance and high extension responses for the sealants.

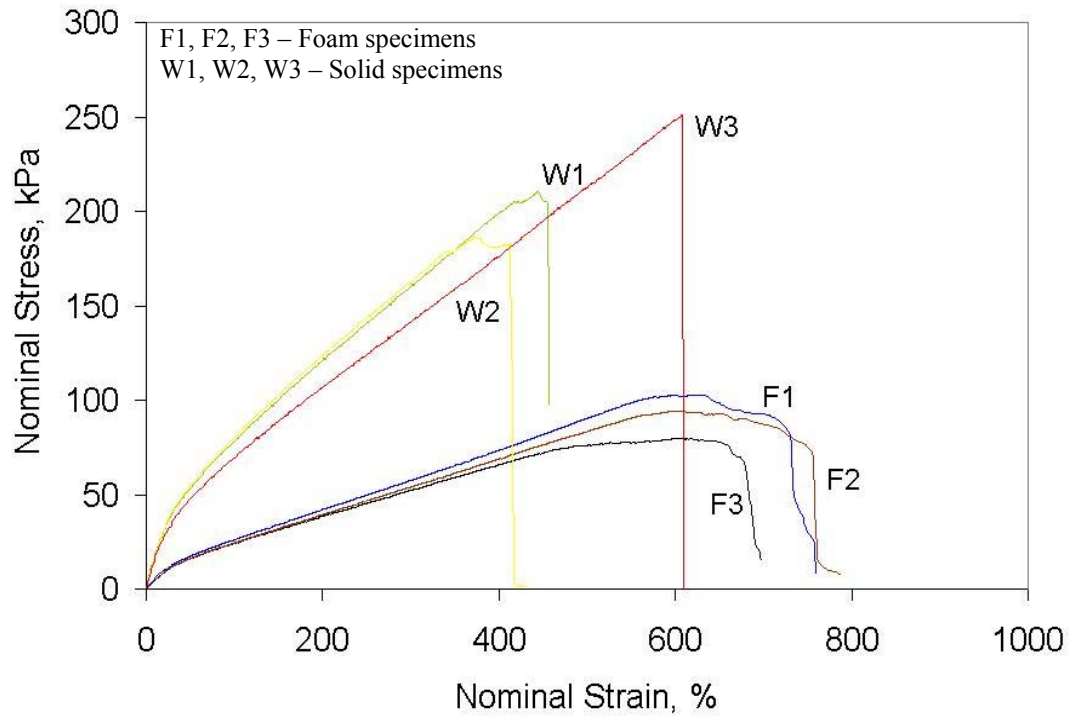


Figure 29. Tensile behavior of Foam sealant and Solid sealant.

Table 4 summarizes the results from the tests performed on these sealants. The nominal ultimate strains for the three samples tested range from 597 % to 608 % for the foam sealant and from 374% to 607% for the solid sealant. The ultimate stress for the foam sealant varies from 80 kPa to 103 kPa and for solid sealant from 186 kPa to 251 kPa. It was observed that both sealants followed the similar non linear stress-strain trend. However, they showed a significant difference in the magnitude of the tensile stress developed. The average 100% modulus value (25 kPa) of three foam sealant specimens is found to be nearly 3 times less than that of the solid sealant (76 kPa). The lower stresses are important for maintaining the bond between the sealant and the concrete; at a given gap displacement, the foam-concrete interface will experience about 1/3 of the stress as that of the solid sealant. Cohesive mode

(failure within material) was observed to be the dominating failure mode for both types of sealants during the tension test.

Table 4. Summary of Stress, Strain and Failure Mode Results from Tension Tests

Sealant	Specimen Designation	Ultimate Nominal Strain, (%)	Ultimate Nominal Stress, (kPa)	Modulus @ 100 % Strain (kPa)	Failure Mode
Foam Silicone	F1	597	103	26	Mixed
	F2	608	94	24	Cohesive
	F3	604	80	24	Cohesive
	Average	603 ± 13^a	92 ± 30	25 ± 3	-
Solid Sealant	W1	444	210	79	Cohesive
	W2	374	186	80	Cohesive
	W3	607	251	69	Mixed
	Average	475 ± 296	216 ± 81	76 ± 14	-

^a95% confidence interval for the average.

5.1.2 Loading and Unloading Test Results

Figure 30 shows loading and unloading behavior of sealants in simple tension for five consecutive cycles. Upon unloading the sample attains its original undeformed shape. The observed elasticity is entropy-driven in nature and elastic force is due to changes in the conformational entropy (James and Guth, 1942). The long chain molecules are stretched out to statistically less favorable states which gives rise to an elastic recovering force that tends to reduce the value of end to end distance of chains to that corresponding to maximum entropy which corresponds to undeformed state. There are also some hysteresis effects. The hysteresis was found to be more significant in the first loading-unloading cycle. This phenomenon, common to most rubbers (Medalia and Kraus, 1994), may be attributed to the delayed relaxation of chain ends that occurs when the sample is deformed. In foams, an additional process of gas diffusion in and out of the cells can add to the hysteresis.

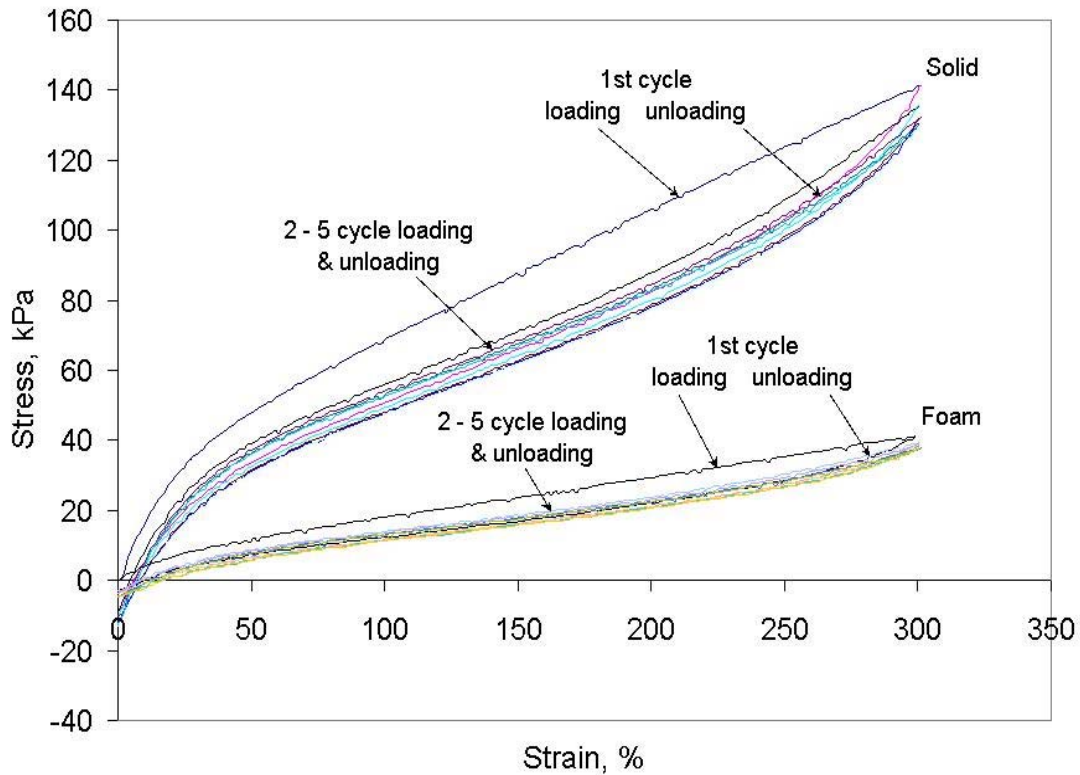


Figure 30. Tension loading and unloading.

It is observed that when a sealant specimen is stretched after the first cycle, the second stress–strain curve lies below the first one. The phenomenon is called the stress softening which may be attributed to more than one mechanism. One of these is simply incomplete elastic recovery (Mullins, 1969). Another mechanism is the progressive detachment, or breaking of network chains attached to filler particles (Bueche, 1960). (All silicones are filled with silica particles.) According to this mechanism, known as the Mullins effect, during the first extension, chains pull free from the filler particles. In the second and subsequent extensions, these chains are no longer supporting stress and the sealant is softened. In our tests, the stress-strain curves followed almost the same path as the one corresponding to the 2nd extension in agreement with the Mullins hypothesis. The hysteresis

effect is observed to be more pronounced for the solid sealant than the foam sealant, but the stresses levels are also higher.

5.2 COMPRESSION TEST RESULTS

5.2.1 Loading Test Results

Figure 31 shows the compression behavior for the two types of sealants (foam sealant and solid sealant). As expected, it was observed that the compressive stresses developed in the solid sealant were much higher than those in the foam sealant. The average compression moduli at 50 % strain were 26 and 193 kPa for the foam and solid sealants, respectively.

5.2.2 Loading and Unloading Test Results

Figure 32 shows sealant behavior when they were repeatedly loaded and unloaded in compression. Hysteresis effects are observed in case of both sealants with no residual stress being developed when the sealant reached their original uncompressed state (zero strain). The hysteresis effect is observed to be smaller in case of the foam sealant compared to the solid sealant.

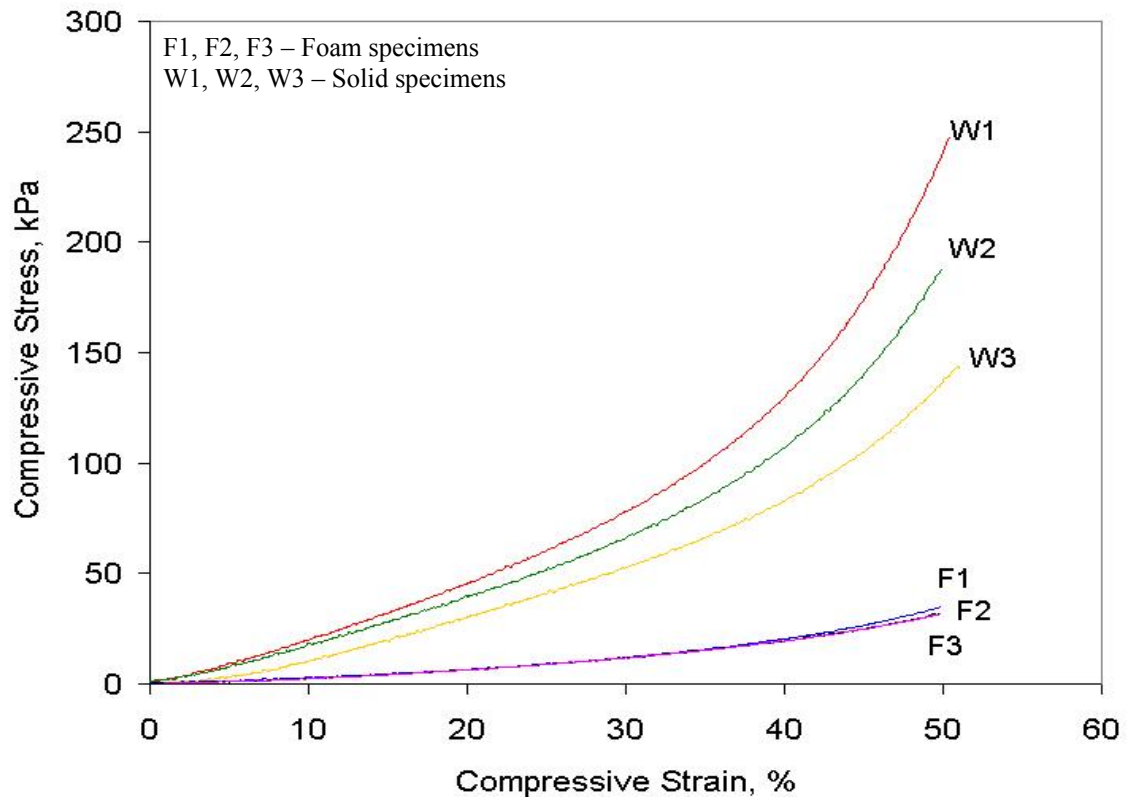


Figure 31. Compression behavior of sealants.

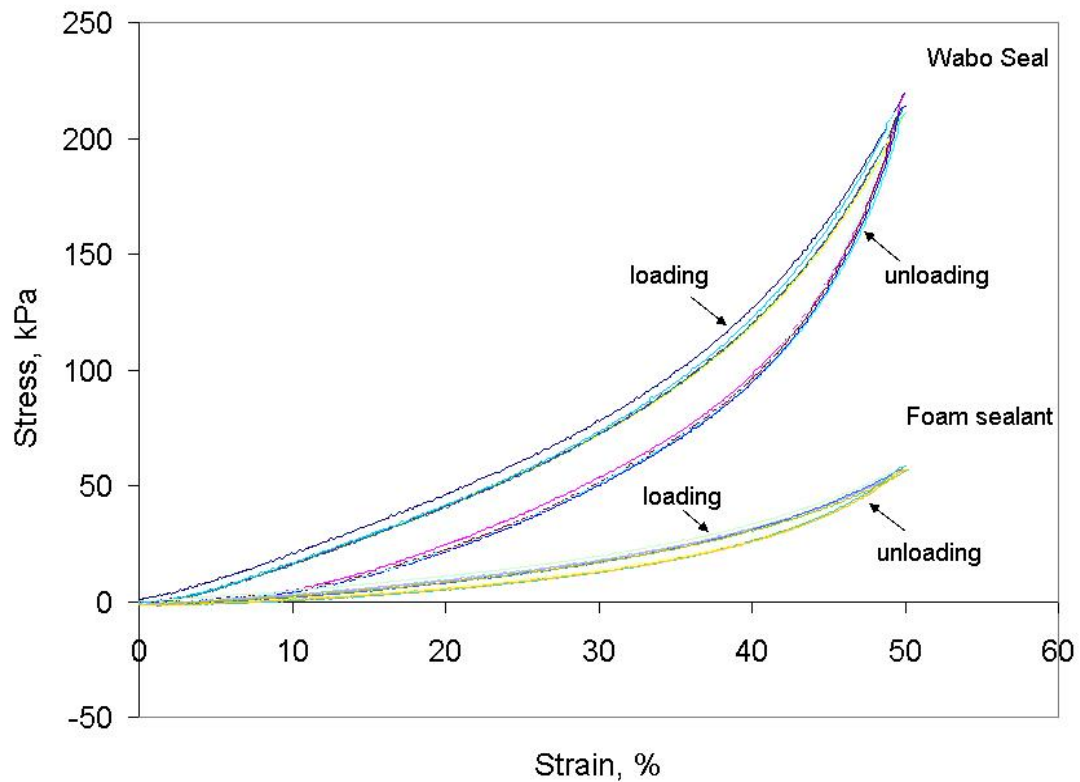


Figure 32. Compression loading and unloading.

5.3 SHEAR TEST RESULTS

Figure 33 shows the stress strain behavior of each sealant type under simple shear. Table 5 presents the test results. For rubber elastomers subjected to shear deformation, the theory of linear relationship of stress and strain (neo-Hookean behavior) is in good agreement with the experimental results up to a shear strain (γ) of about 1.0 (Treloar, 1970). The average elastic shear modulus of the foam sealant was found to be 11.43 kPa. The corresponding value for the solid sealant was 23.42 kPa. For shear strain values greater than 1.0, the sealants were no longer observed to remain under simple shear but are subjected to a more complex deformation due to the finite size of the sample.

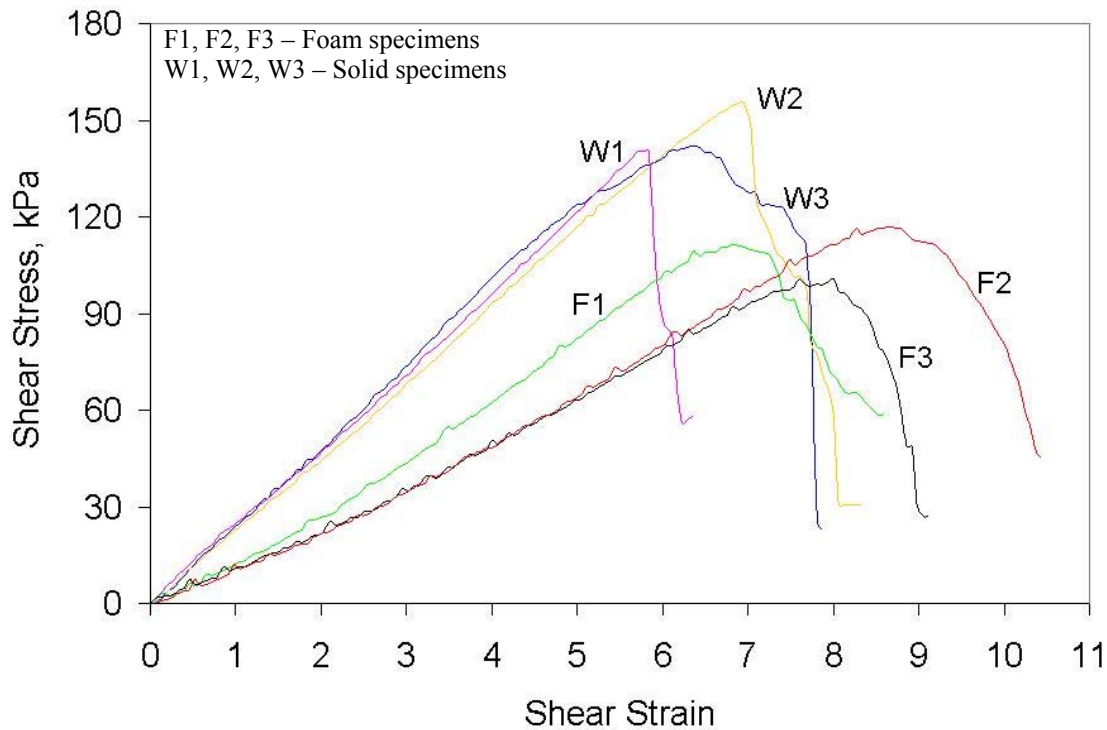


Figure 33. Simple shear test results.

Table 5. Results of Shear Test

Sealant	Specimen Designation	Shear Modulus, (kPa)	Ultimate Deformation, (mm)	Ultimate Force, (N)	Failure Mode
Foam Sealant	F1	12	55	302	Cohesive
	F2	11	48	261	Cohesive
	F3	12	43	287	Cohesive
Wabo Seal	W1	24	37	363	Adhesive
	W2	22	44	401	Mixed
	W3	23	40	367	Mixed

5.4 SALT WATER IMMERSION TEST RESULTS

Figure 34 presents the results of tension test on salt water immersed and dry foam sealant specimens showing effects on the two performance indices modulus and extensibility. Similar results for the solid sealant are presented in Fig. 35. Figure 36 shows comparison between the tensile properties of these two sealant types after immersion in salt-water solution for 2 weeks.

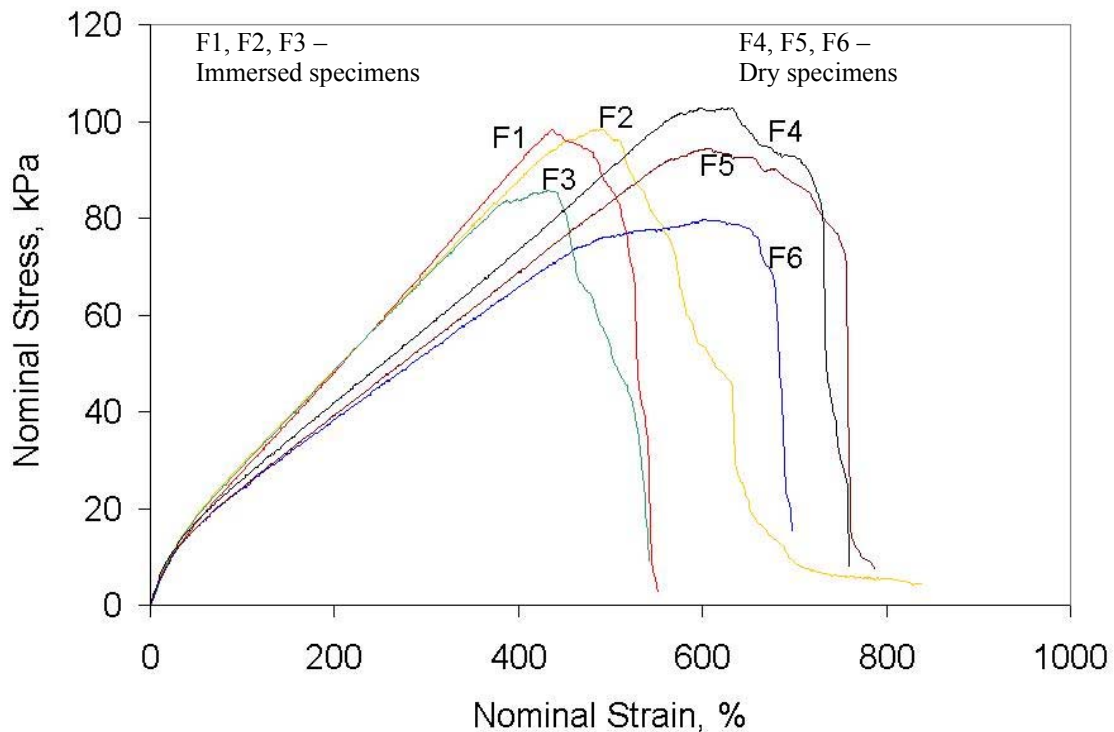


Figure 34. Effects of salt water immersion on foam sealant.

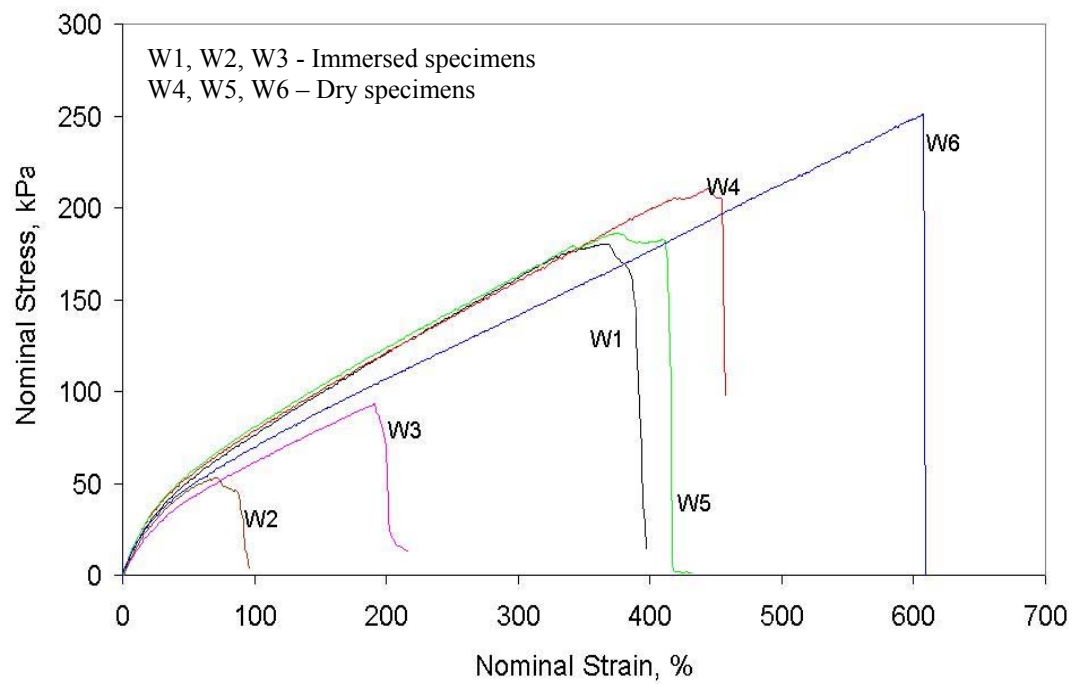


Figure 35. Effects of salt water immersion on solid sealant.

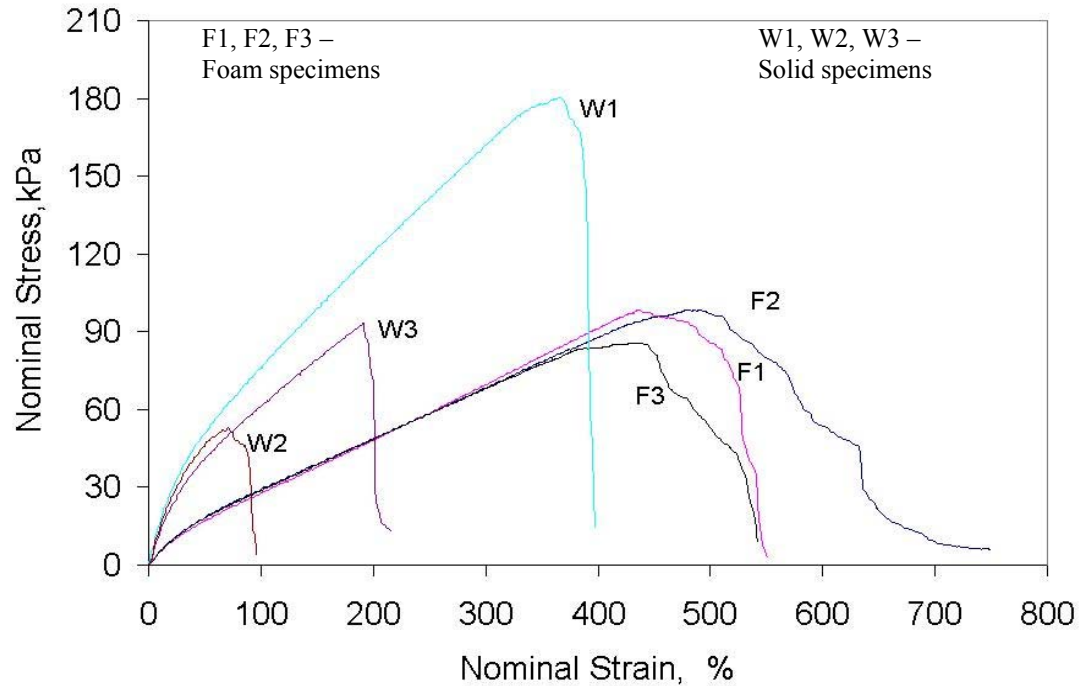


Figure 36. Comparison of effects of salt water on foam sealant and solid sealant.

Table 6 presents the results of tension tests on salt water immersed samples of both foam sealant and solid sealant. Table 7 compares mean 100% modulus and mean ultimate elongation values of salt-water-immersed samples with those obtained from the tension test on dry samples (Table 4 and Figure 30). Both dry and immersed samples were prepared at the same time and hence the results for these two samples have been compared assuming equal variances. It can be observed from the results presented in Fig. 34 and Table 7 that there is decrease in the extensibility of foam sealant with immersion, from the average ultimate elongation value of 603% (for dry specimen) to the value of 453% (salt water immersed specimen). A two-tail t-test was performed to determine if this observed difference in the mean extensibility of immersed and dry samples was a chance finding or not. The test resulted in a t-value of 7.9 and a probability of 0.0014. Thus, the extensibility difference between two groups was not likely to have been a chance finding and they are statistically different. The modulus of foam sealant at 100% strain was found to have increased by about 15% after immersion. The reason for this might be that the curing of the specimen was enhanced after immersion (Beech, 1988). With enhanced curing, density of crosslinking increases which is manifested by increase in the measured modulus. The comparison of failure modes observed for dry and immersed foam sealant specimens did not show any evidence of bond loss between the sealant and concrete substrate even at the ultimate elongation.

For the solid sealant, however, the effects of the immersion appeared to weaken its bonding characteristic. As can be seen in Figure 35 and Table 6, two out of three specimens (W2 and W3) showed total adhesion failure (complete separation of sealant from substrate) during the tensile test. These failures occurred at relatively small strain values of 191%

(specimen W3) and 71% (specimen W2). The third specimen (W1) showed the mixed failure (partly cohesive and partly adhesive) at 366% elongation value. The diffusion of salt water along the sealant-substrate interface is a possible reason for the weakening of the sealant bond to the joint surface (Beech, 1988). The measured values showed an apparent 10% decrease in the 100% modulus of the solid sealant due to immersion, but this change was not statistically significant. It should be noted here that the sealant joints were prepared without using primers. Primers may affect the bonding of the foam and solid sealants with the substrate by different amount, and hence could yield different bonding test results than reported herein.

Table 6. Stress, Strain and Failure Mode Results from Salt Water Immersion Test

Sealant	Test Condition	Specimen Designation	Strain (%)	Stress (kPa)	100 % Modulus (kPa)	Failure Mode
Foam Silicone	Immersed	F1	437	98	27.7	Mixed
		F2	491	98	29.3	Cohesive
		F3	433	86	28.7	Cohesive
		Average	453 ± 81 ^a	94 ± 17	28.5 ± 2.0	-
Solid sealant	Immersed	W1	366	180	76	Mixed
		W2	71	53	No result	Adhesive
		W3	191	93	61	Adhesive
		Average	209 ± 368	108 ± 168	-	-

^a95% confidence interval for the average.

Table 7. Salt Water Immersion Effects on Sealant Modulus and Extensibility

Sealant	Test Condition	Average Ultimate Strain (%)	Average Ultimate Stress (kPa)	Average 100 % Modulus (kPa)	Extensibility Difference (%) *	Modulus Difference (%) *
Foam Silicone	Dry	603	92	24.8	0	0
	Immersed	453	94	28.6	-25	+15
Solid sealant	Dry	475	216	76.1	0	0
	Immersed	209	109	68.8	-56	-10

* Note: + indicates increase and – indicates decrease from dry specimen tension test results

5.5 BOND (OVEN AGED) TEST RESULTS

Upon visual observation, no specimens were found to develop any crack, separation, or other opening in the sealant or between the sealant and the concrete test blocks. For each of the five extensions, 100 % modulus (the sealants stress at 100% strain) values have been plotted in Fig. 37, which depicts the fatigue of material with tensile deformation after oven aging and cooling cycles. These values are summarized in Table 8. From these values, it is seen that the 100% modulus of both sealant types changed by small amounts with each subsequent extension in the course of five extensions. Figure 38 shows the stress-strain plot for the 5th extension of the sealants. This plot represents a typical of stress-strain curve observed during each extension. Comparison of mean 100% modulus values between the first and the fifth extension shows a modulus decrease of 13% and 7% for the foam and the solid, respectively. Both of these changes were not statistically significant. However, the trend with cycle for the foam has a t value of 3.9 for a probability of 0.05 at 3 degrees of freedom. For the solid, the probability level is 0.17, which we do not consider significant.

Table 8. Modulus under Repeated Extensions from Bond Test after Oven Aging

Sealant	Specimen Designation	Modulus @100 % Strain (kPa)				
		1 st Extension	2 nd Extension	3 rd Extension	4 th Extension	5 th Extension
Foam Silicone	F1					
	F2	35	33	31	31	31
	F3	33	31	30	29	29
		28	27	23	24	25
	Average	32 ± 9.0 ^a	30 ± 7.0	28 ± 11.0	28 ± 9.0	28 ± 8.0
Solid sealant	W1	88	82	81	79	83
	W2	88	81	80	78	79
	W3	70	66	65	68	67
	Average	81 ± 25.0	76 ± 21.0	75 ± 22.0	75 ± 15.0	76 ± 20.0

^a95% confidence interval for the average.

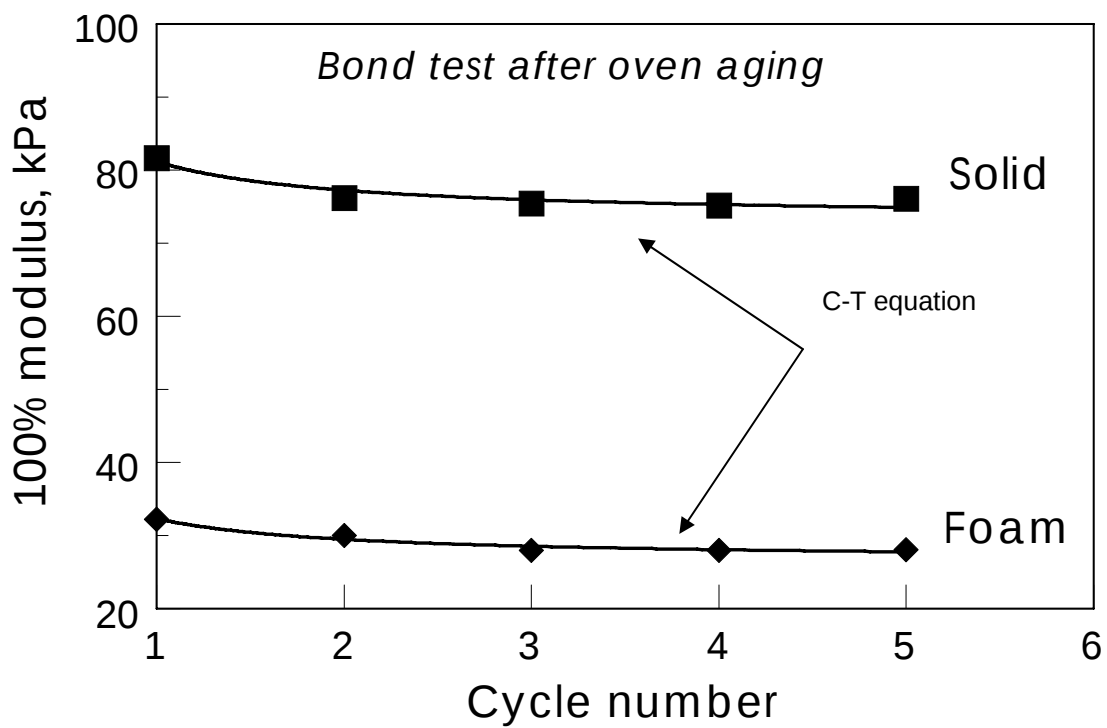


Figure 37. Fatigue of sealants with tensile deformation after oven aging and cooling cycles. Curves are simplified C-T equation

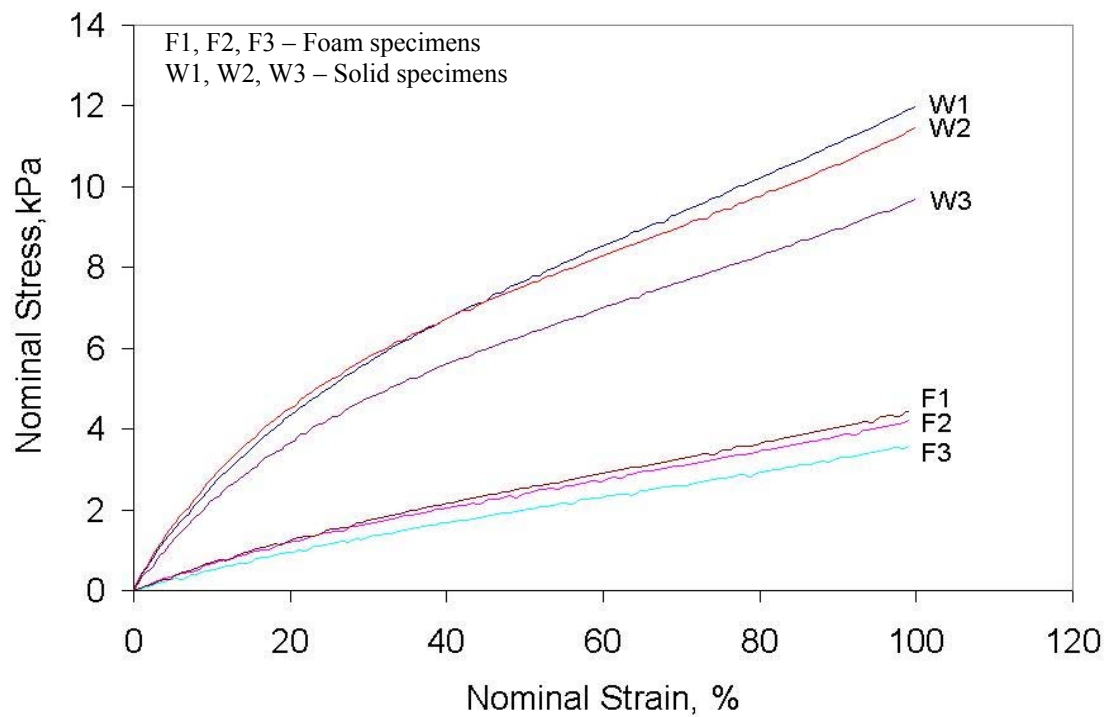


Figure 38. Bond Test: Stress-Strain at 5th extension.

In Fig. 37, C-T equation (Eq. 8) has been used to describe the loss of sealant modulus with tensile deformation after oven aging and cooling cycles. The parameters of the model equation were calculated by nonlinear regression analysis using commercially available software SigmaPlot 9.0 (Systat Software Inc., 2004). The value of m was set at 1.0. The values of E_{∞} are 26.7 kPa and 73.3 kPa for the foam and solid sealant respectively. The values of a , which represents the decay “time” (number of cycles) are 0.21 ± 0.09 and 0.11 ± 0.07 for the foam and solid respectively, where the errors are the 95% confidence limits of the values. Comparing these two values using Student’s t -test gives a t -value of 2.8 and a probability of 0.03. Thus the two rates of decay are different at the 97% probability level. The foam sealant, therefore, appears to be more resistant to fatigue than the solid sealant, based on the available data. Our interpretation of this is that the lower modulus of the foam results in less stress at the fixed strain, and thus less fatigue.

5.6 STRESS RELAXATION TEST RESULT

Figures 39 and 40 respectively show stress relaxation test results in tension and compression that have been reduced by Eq. 10 to obtain relaxation times. During stress relaxation in tension, stress decreased from the initial value of 27.62 kPa to 20.91 kPa for the foam and from the initial value of 92.68 kPa to 82.76 kPa for the solid in 24 hour period. Hence, relaxations of two sealants are calculated using Eq. 9 as 25% and 10% respectively after total test duration of 24 h. A sharp decrease in the stress was observed to take place within small initial test period of 1 hour beyond which rate of stress decay was gradual (Fig. 39). For example, for the foam, stress drop within initial 1 hour was 4.4 kPa whereas the drop was 2.31 kPa for the subsequent 23 hours period. For the solid, corresponding drops were

6.44 kPa and 3.48 kPa respectively. It was also observed that after the 16-hour period, the stresses appeared to remain more or less steady for both sealants depicting the achievement of equilibrium. During stress relaxation in compression, stress dropped from the initial value of 70.00 kPa to 19.83 kPa for foam and from the initial value of 254.1 kPa to 227.7 kPa for solid in the test period of 24 hours. Corresponding relaxations are found to be 70% and 10% from Eq. 9. As observed in stress relaxation in tension, the majority of stress decay in compression also occurred in initial small period after which the rate of decay was gradual. For the foam, the stress decay during the first 1 hour was 23.64 kPa, and the decay during next 23-hour test period was 26.53 kPa. Similarly, corresponding stress drops for the solid were 19.4 kPa and 7.0 kPa.

The stretched exponential form of the relaxation modulus $E(t)$ given by Eq. 10 was used in the Fig. 39 and Fig. 40 to model the isothermal stress relaxation behavior of sealants. The parameters for foam and solid sealants for different relaxation test modes (tension and compression) have been presented in Table 9. These parameters were calculated according to the Eq. 10 using SigmaPlot 9.0 graphing software. The values of relaxation constant τ in tension test are 0.91 ± 0.02 h and 0.93 ± 0.02 h for the foam and solid, respectively, where the errors are the 95% confidence limits of the values. The t -test for these two values gives a t -value of 0.4 which indicates that the difference between these two values is not significant.

Table 9. KWW Equation Parameters for Stress Relaxation Test

Sealant	Relaxation Test Mode	β	E_0 , kPa	E_∞ , kPa	τ , h
Foam Silicone	Tension	0.3	28.7	20.4	0.91 ± 0.02
	Compression	0.55	75.8	20.8	2.2 ± 0.04
Solid sealant	Tension	0.36	93.5	82.2	0.93 ± 0.02
	Compression	0.17	254.6	208.6	41.4 ± 0.77

Therefore, two sealants are found to exhibit approximately same decay rate in tensile elongation. For compression relaxation, however, large difference between relaxation times is observed. The values of relaxation constant τ are 2.2 ± 0.04 h and 41.4 ± 0.77 h for the foam and solid, respectively in this case. Comparing these two values gives a t-value of 3.04. Thus, two relaxation time values are statistically different and it appears that the stress in the foam sealant gets relaxed much faster than the stress in the solid sealant. It should be noted herein that because the relaxation tests were performed in tension and compression mode rather than shear mode, there might have been the gain or loss of air in the foam sealant bubbles during prolonged exposure of the specimen to constant strain condition. As a result, the relaxation behavior observed for the foam sealant in our case might not be due purely to the material response alone.

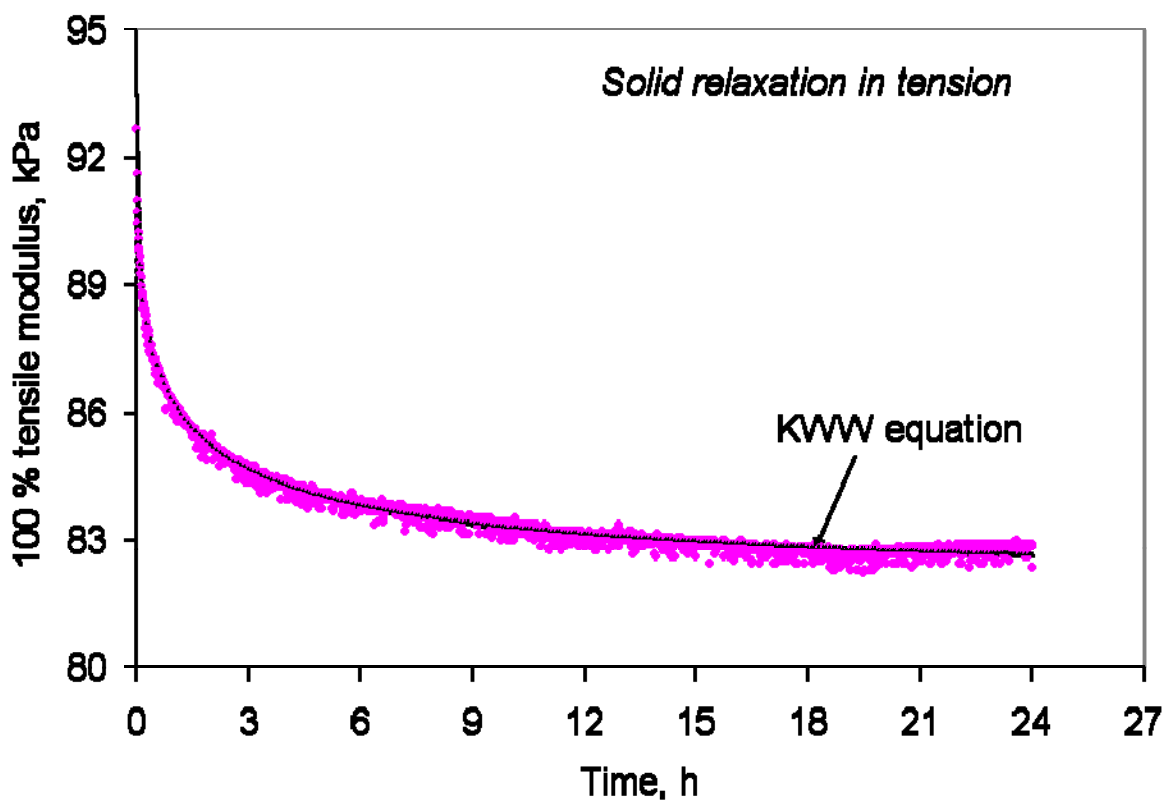
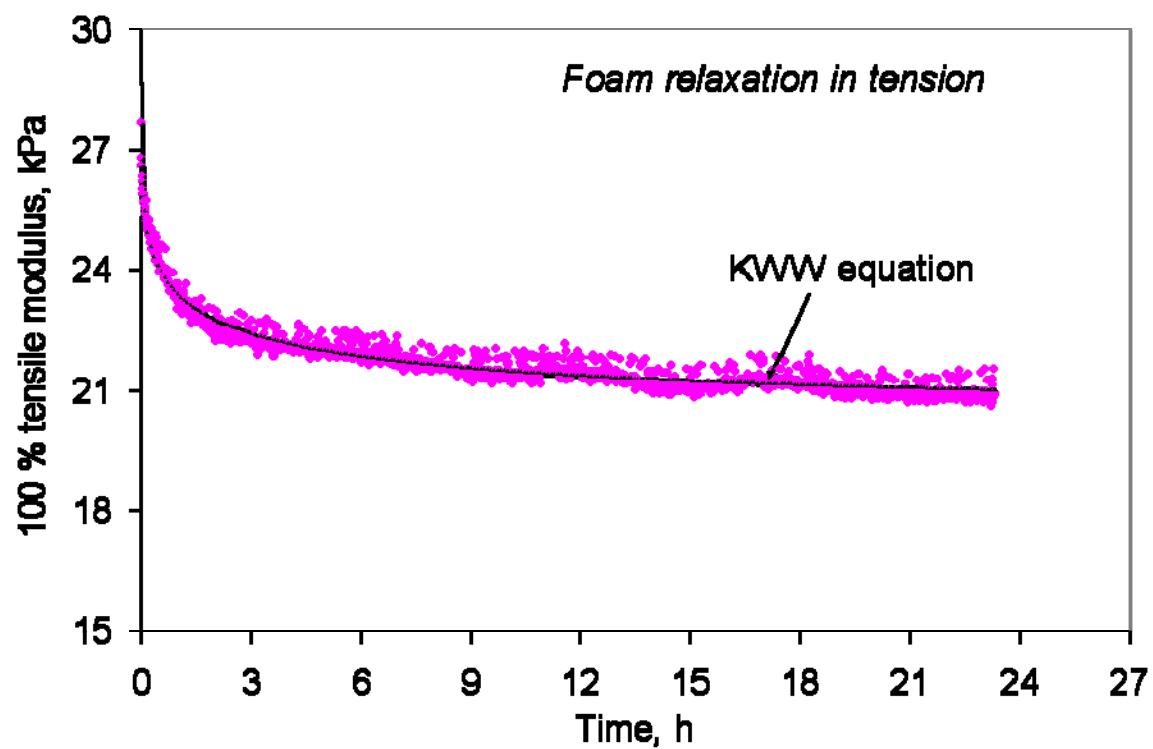


Figure 39. Isothermal stress relaxation in tension for foam and solid. Curves are KWW equation.

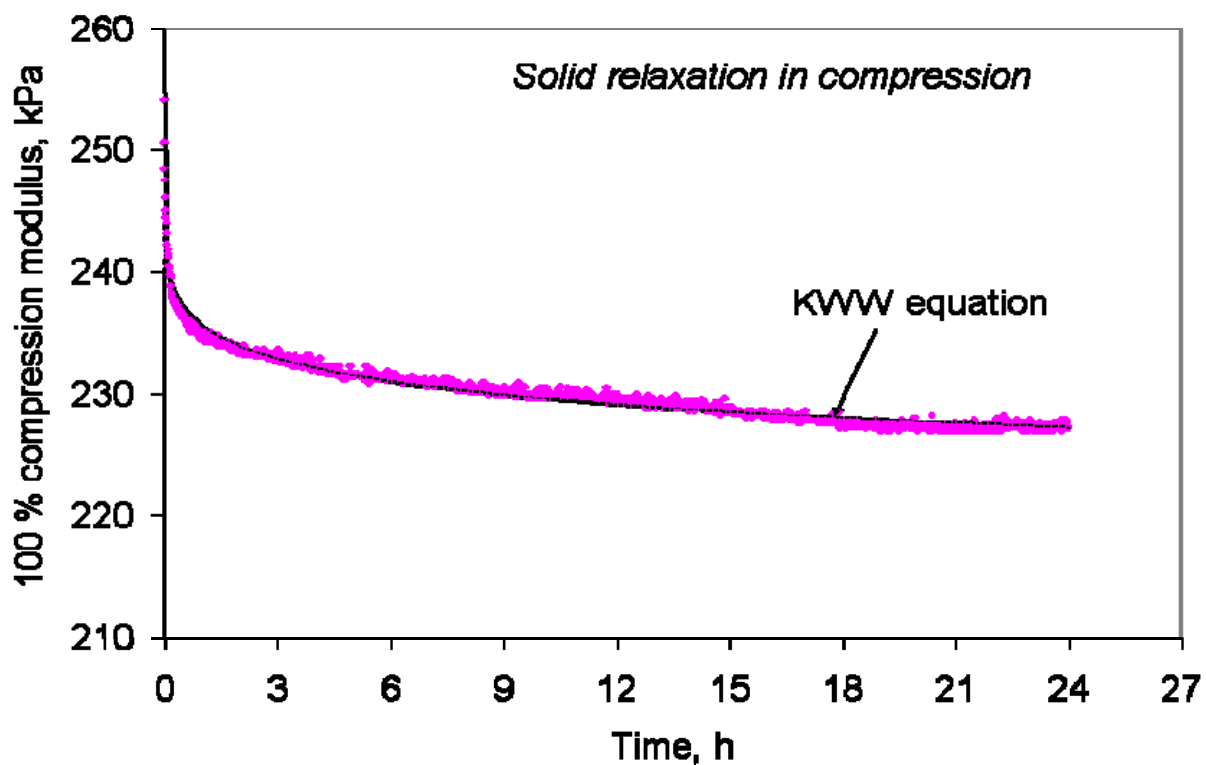
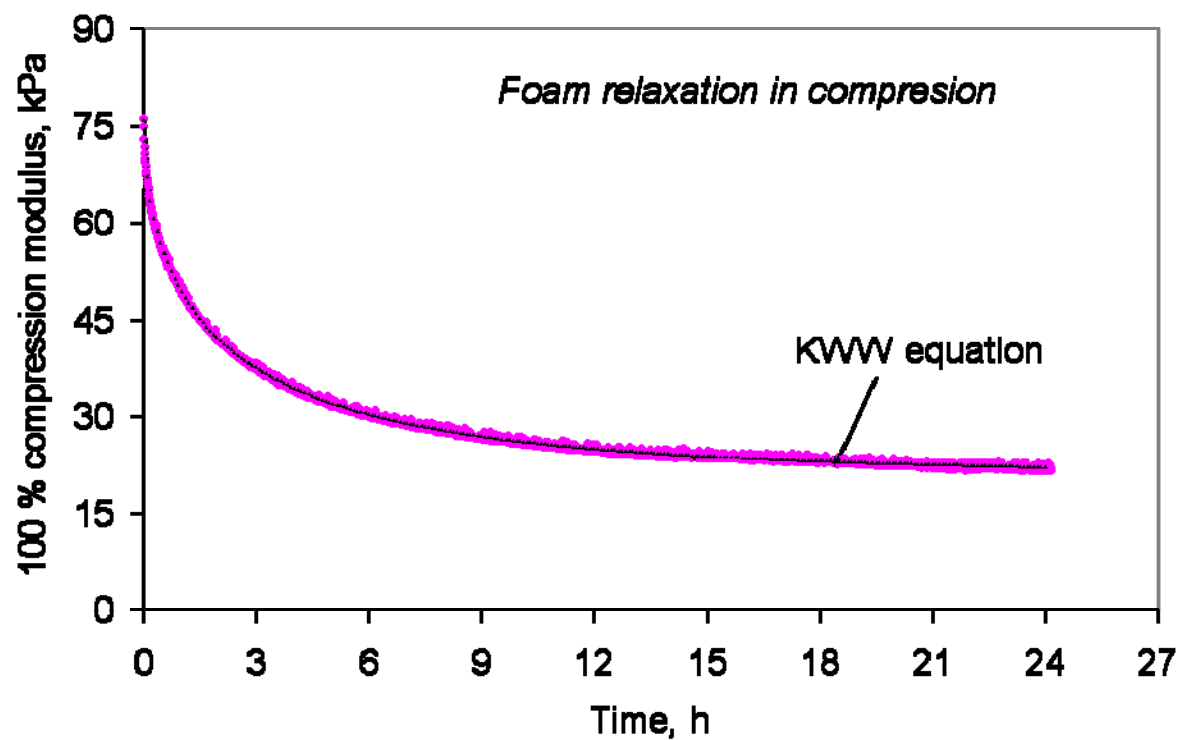


Figure 40. Isothermal stress relaxation in compression for foam and solid. Curves are KWW equation.

5.7 CREEP TEST RESULTS

Deformation of foam and solid with time under constant tensile load are presented in Fig. 41. Creep for foam and solid after 24 hours were calculated using Eq. 11 as 21% and 15%, respectively.

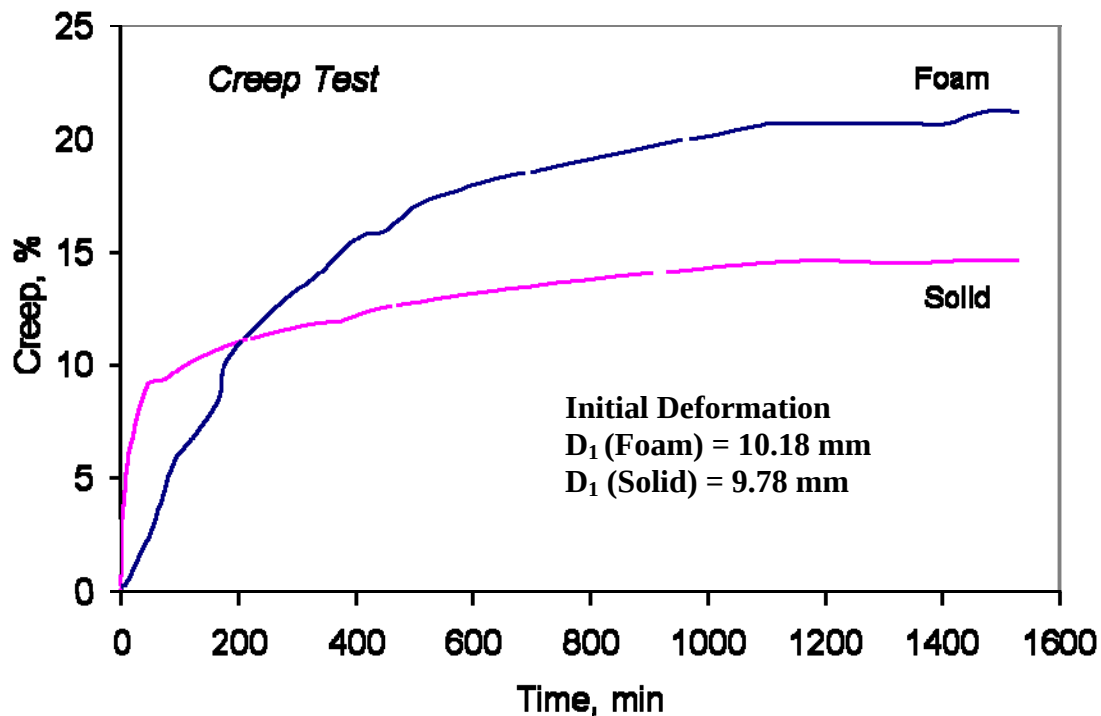


Figure 41. Creep deformation of foam and solid in tension.

5.8 COMPRESSION RECOVERY TEST RESULTS

Figure 42 shows the test results after the sealants have been released from the compressed state. Foam sealant was observed to undergo a permanent set of nearly 20% of initial compression while solid sealant showed as little as 1.5% set. The percent value in case of the foam sealant seems to be substantially larger than that for the solid sealant, however; it was the value observed just 1 hour after the release of sealant from compression. During the

prolonged compression of the foam, air is forced to escape from the foam bubbles. Upon release of compression, there is a backflow of air into these bubbles from the surrounding and it may take significantly longer time than just 1 hour to complete the process of the regaining of air by the foam bubbles. Hence, the set observed for the foam sealant may not be the permanent in nature. Recovery attained by the foam sealant is about 90% of its original width/length, whereas, it is almost 100% for the solid sealant. It is also observed that for both sealants, almost all recovery takes place within the first five minutes after the sealants have been released from compression.

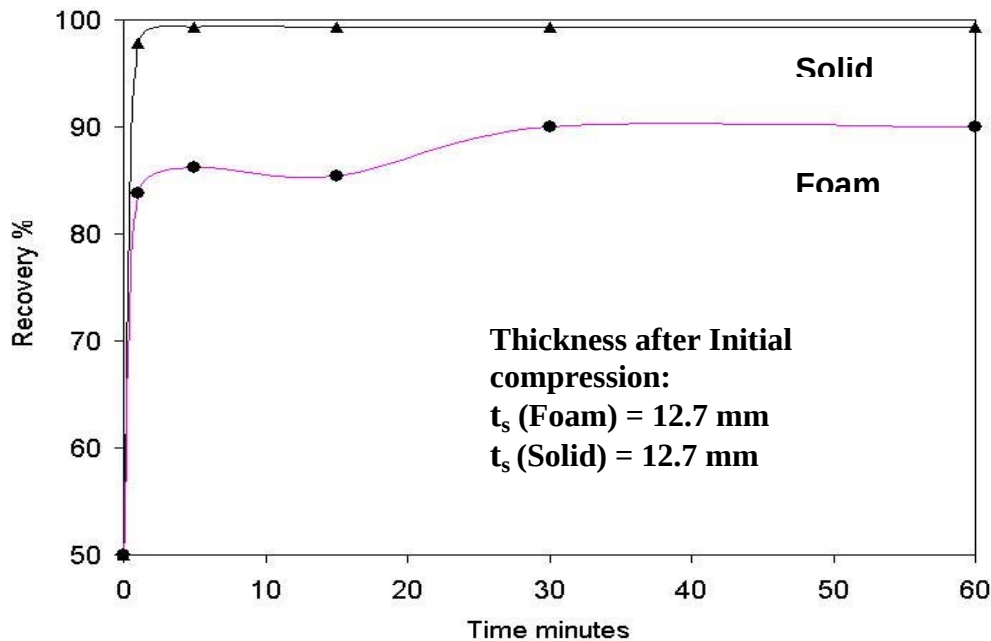


Figure 42. Compression recovery of sealants.

5. 9 TEMPERATURE SENSITIVITY TEST RESULTS

5.9.1 High and Low Temperature Effects Test Results

The effects of exposing sealants to low and high temperature extremities on their important tensile properties, namely ultimate elongation and modulus, and their bonding

integrity with the joint substrate have been presented herein. Figure 43 shows stress-strain curves from the tension test on foam and solid samples which have been subjected to high temperature (70 °C) exposure. Similar results for samples exposed to low temperature (-36 °C) are presented in Fig. 44. Numerical values of test results are summarized in Table 10. These test results are also compared with results obtained from tension test that were performed on the same aged foam and the solid sealant samples cured at standard laboratory conditions ($23 \pm 2^\circ \text{C}$).

Table 10. Stress, Strain and Failure Mode Results from Temperature Sensitivity Test

Sealant	Exposure condition	Specimen Designation	Ultimate Nominal Strain, (%)	Ultimate Nominal Stress, (kPa)	Modulus @ 100% Strain,(kPa)	Failure Mode
Foam Silicone	High Temp	F1	350	87	32	Cohesive
		F2	306	64	30	Adhesive
		F3	275	65	31	Cohesive
	Average		310±94 ^a	72±33	31±3.0	
	Low Temp	F1	204	45	26	Adhesive
F2		457	78	22	Cohesive	
F3		427	51	19	Adhesive	
Average		363±343	58±44	22.5±8.0		
Solid Sealant	High Temp	W1	335	207	93	Adhesive
		W2	240	161	91	Adhesive
		W3	225	150	92	Cohesive
	Average		267±148	173±76	92±4.0	
	Low Temp	W1	208	93	59	Adhesive
W2		472	182	65	Cohesive	
W3		640	206	60	Adhesive	
Average		440±541	160±148	61±8.0		

^a95% confidence interval for the average.

Table 11 presents mean 100% modulus and mean ultimate elongation values for standard temperature conditioned (Table 4 and Fig. 29) and high and low temperature conditioned samples (Table 10 and Fig. 43 & 44).

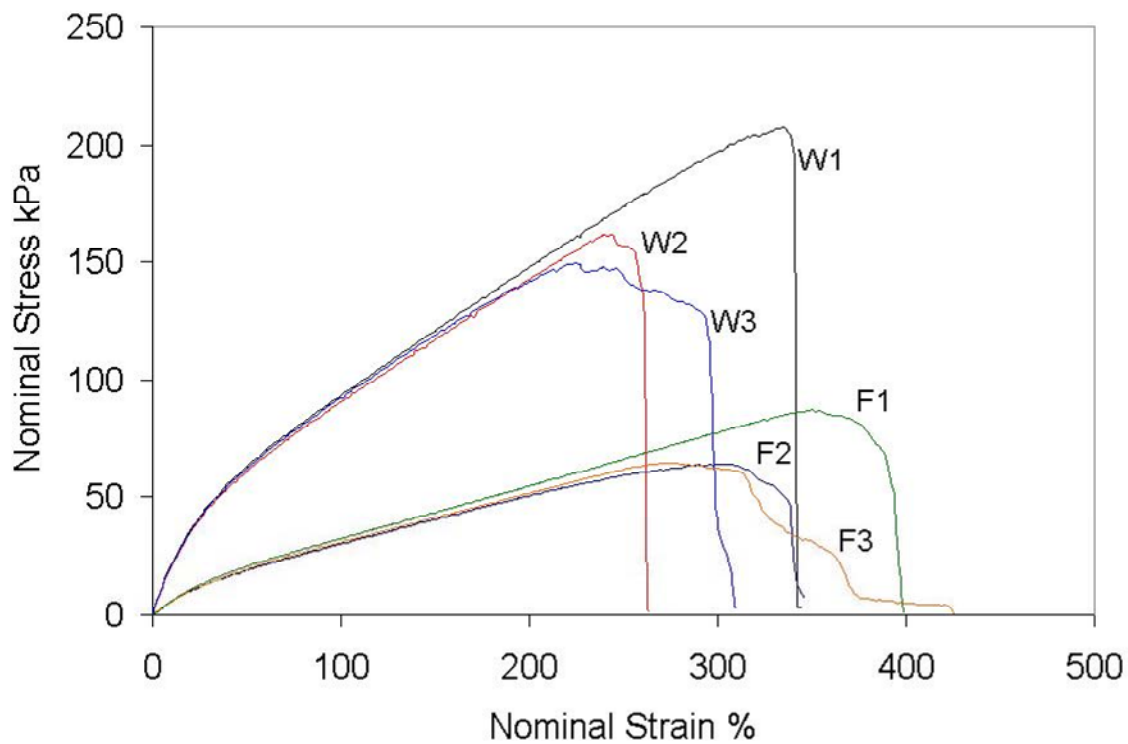


Figure 43. Stress-Strain plot of samples after high temperature conditioning.

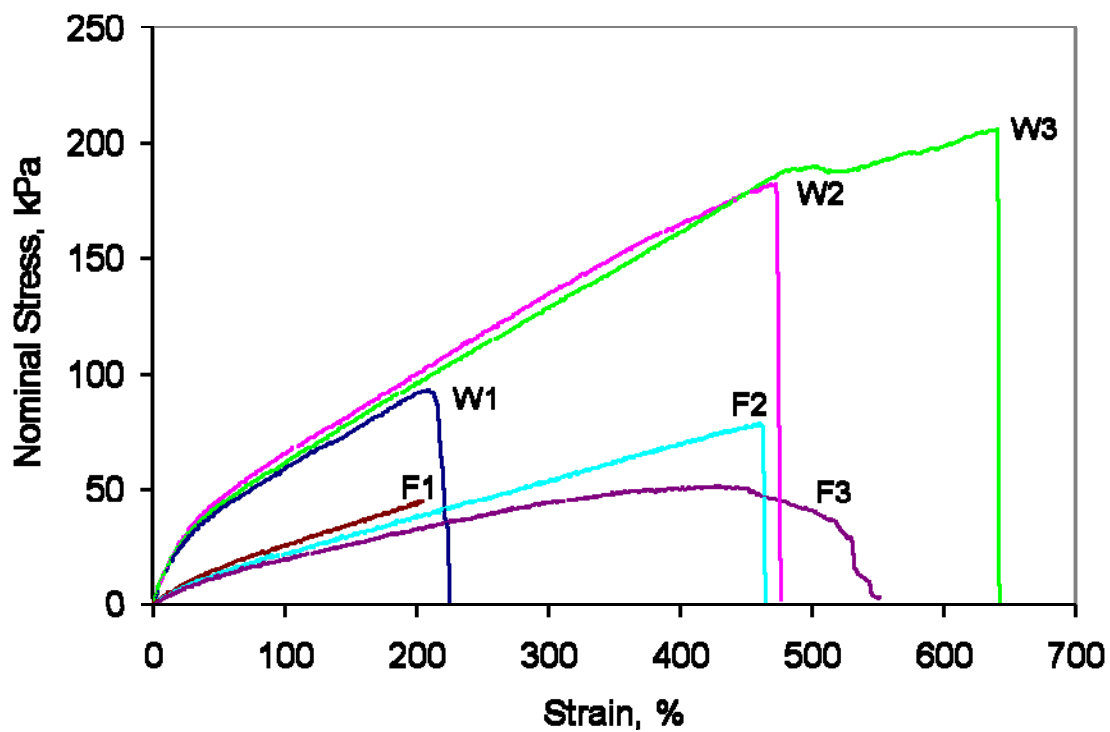


Figure 44. Stress-Strain plot of samples after cold temperature conditioning.

A multivariant linear model (Eq. 13) used in Fig. 45 to model the experimental modulus data which included temperature and material effects as well as effects due to interaction of material with temperature was:

$$E = a_0 + a_1 * X_1 + a_2 * T + a_3 * T * X_1 \quad \text{----- (13)}$$

Where, E = modulus, T = temperature, °C; X1= 1 if foam, zero otherwise.

All parameters a_i were found to be significantly different from zero and are, respectively: 71 ± 5 ; -46 ± 7 ; 0.28 ± 0.1 ; and 0.21 ± 0.16 . Figure 45 shows the results of multivariant linear model for material effects and interaction of material with temperature which suggests that high temperature conditioning of the sealant increases the modulus of sealants. It is also observed that slope of the solid is greater than foam. The oven aging has appeared to assist the curing process of sealants which become apparent in increase in measured modulus of sealants. It was observed that majority of foam specimens failed cohesively; however, adhesive failure mode was observed for most of solid specimens. The stress-strain plot results (Fig. 29) from the tension test makes it clear that the solid sealant fails at substantially higher levels of stress than the foam sealant. The higher stress levels required to elongate the solid sealant result in very high interfacial stress at the sealant/concrete interface which explains degradation of bond between solid sealant and joint substrate. In contrast, the low modulus, and hence, lower stress levels at foam sealant-concrete interface results in the material failing rather than debonding from the concrete.

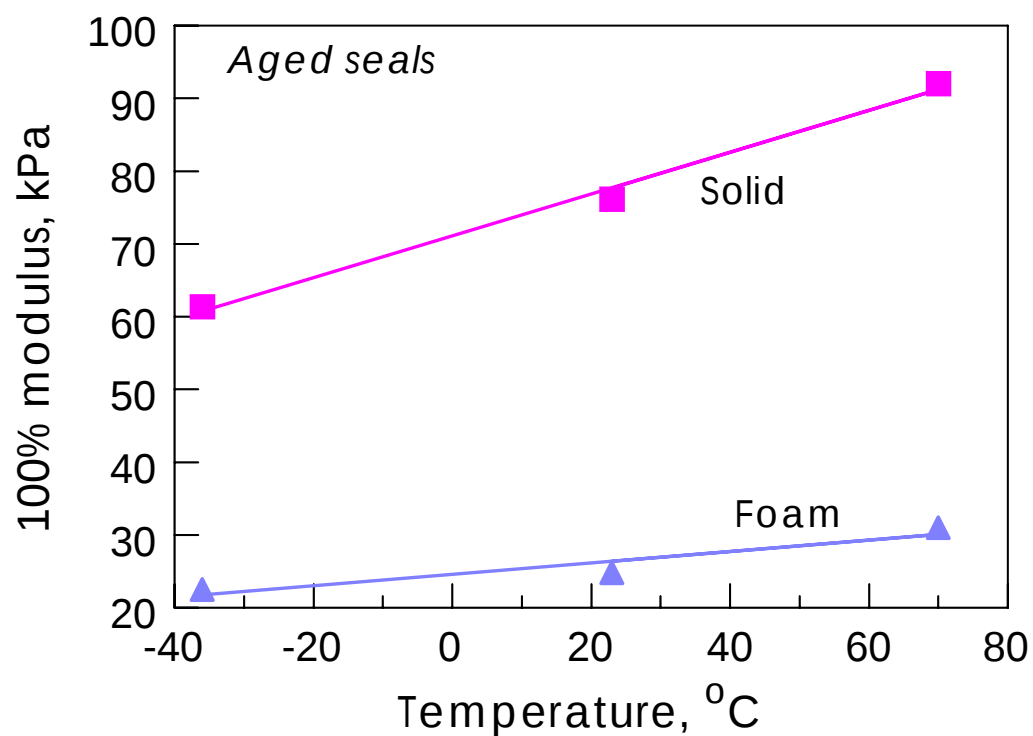


Figure 45. Effects of high and low temperature exposure on sealant modulus. The lines are results of multivariant linear model for material effects and interaction of material with temperature.

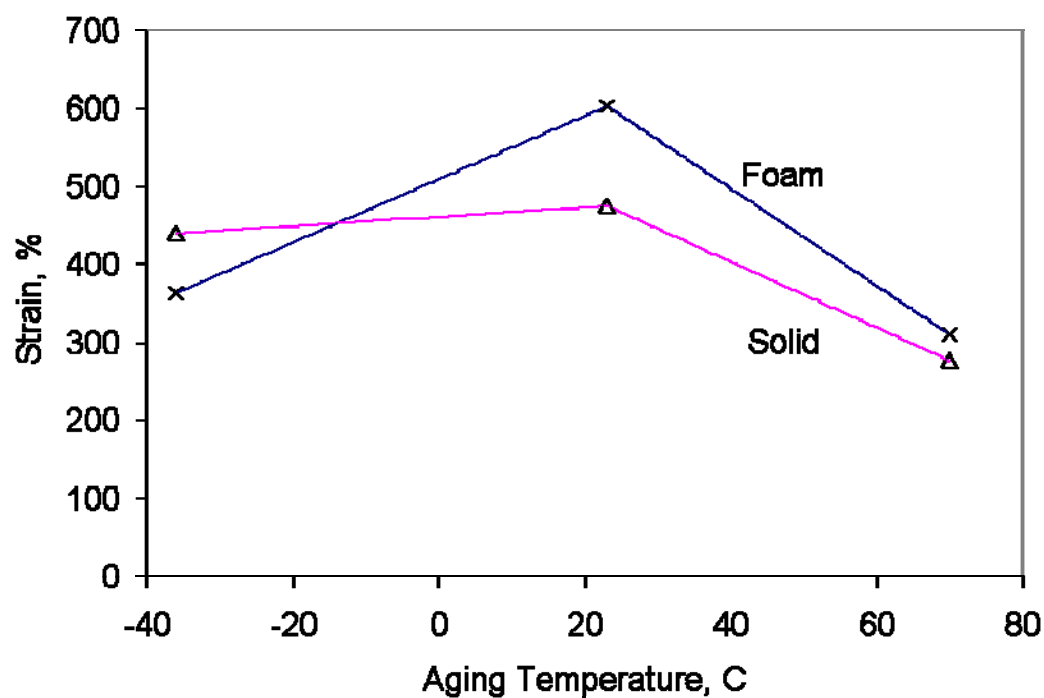


Figure 46. Effects of high and low temperature exposure on sealant extensibility.

Table 11. Temperature Exposure Effects on Sealant Modulus and Extensibility

Sealant	Conditioning Temperature	Average Ultimate Strain, (%)	Average 100% Modulus, (kPa)	Extensibility Difference, (%) *	Modulus Difference, (%) *
Foam Silicone	Standard (23°C)	603	24.80	0	0
	High (70 °C)	310	31.00	-49	+25
	Low (-36°C)	362.7	22.5	-40	-9
Solid Sealant	Standard (23°C)	475	76.13	0	0
	High (70°C)	267	92.05	-44	+21
	Low (-36°C)	440	61.4	-7.3	-19

* Note: + indicates increase and – indicates decrease from standard specimen test results

For sealant elongation, the parameters were not found to be significant suggesting that the material and temperature effects were negligible on sealant elongation. However, a drop in ultimate displacement for two sealants under cold and hot exposure condition was noted (Fig. 46). The magnitudes of ultimate strain drops for low and high temperature conditioned samples compared to standard samples are given in Table 11. The reason for strain reduction at cold temperature is due to the early sealant and substrate bond failure which might be attributed to the diffusion of moisture into the joint interface during cold exposure. Also, maximum percent strain reduction of oven aged sealants might be ascribed to the stiffening of the sealants after high temperature exposure.

5.9.2 Freeze and Thaw Cycle Test Result

The variation of conditioning temperature during one typical cycle of duration 24 hours is shown in Fig. 47. Results of tension test on the foam and solid specimens are presented in Fig. 48 and Table 12.

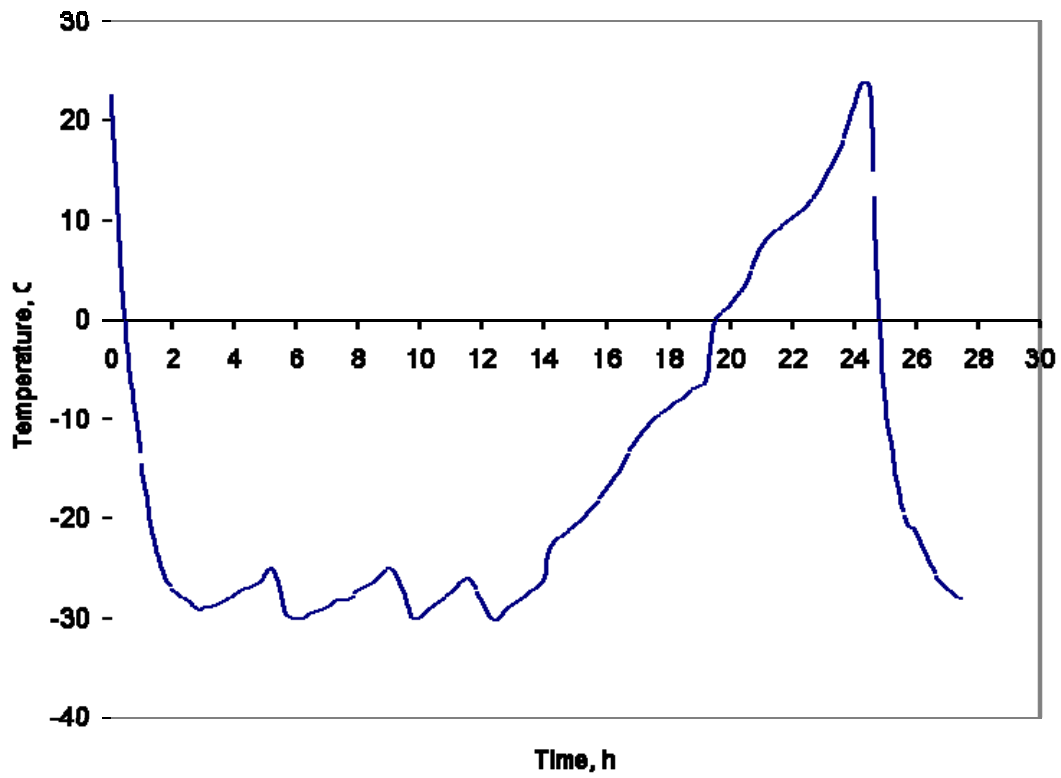


Figure 47. Temperature variation in a single cycle.

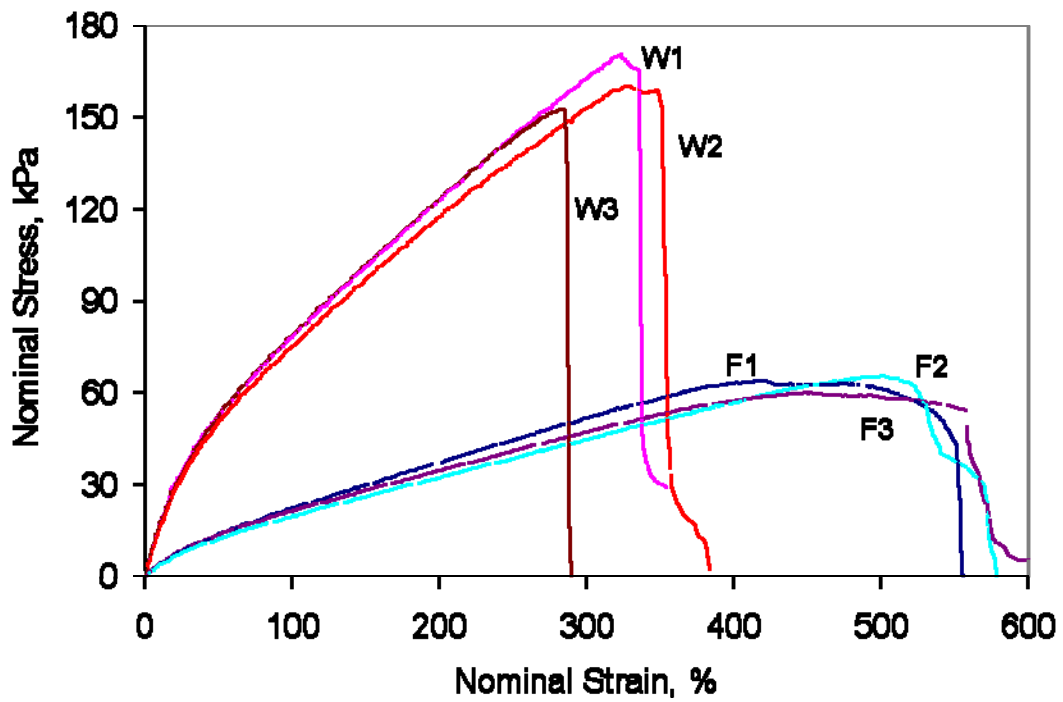


Figure 48. Tension test results of sealants exposed to alternate cold and room temperature.

When we compare them with the results obtained from the tension tests on standard temperature conditioned sealant samples, we see maximum strain percent decrease of 24% and 34% for foam and solid respectively. Modulus of solid sealant is not affected. However, foam sealant is observed to be softened as there is 7% decrease in measured modulus. Separation of sealant from the joint surface is seen to be the most common failure mode among specimens during the tension test.

Table 12. Stress, Strain and Failure Mode Results from Freeze and Thaw Cycle Test

Sealant	Specimen Designation	Ultimate Nominal Strain, (%)	Ultimate Nominal Stress, (kPa)	Modulus @ 100 % Strain (kPa)	Failure Mode
Foam Silicone	F1	420	64	22	Adhesive
	F2	500	65	27	Cohesive
	F3	449	60	20	Adhesive
	Average	456±101 ^a	63±7.0	23±9.0	
Solid Sealant	W1	323	170	78	Adhesive
	W2	327	161	75	Cohesive
	W3	285	153	79	Adhesive
	Average	312±58	161±21	77±5.0	

^a95% confidence interval for the average.

5.10 CURE RATE TEST RESULTS

Figure 49 shows the sealant stress as the function of curing time. Table 13 presents the 100% modulus values achieved by sealants at different curing periods. The results show higher increase in sealant strengths with time up to the period of approximately 3 days which suggests rapid curing of sealant in the initial period. During this initial 3-day period, sealants were observed to develop nearly 64% of their 21-day strength, a value that has been assumed to be the full-cured sealant strength. The increments in sealant strength were small after this period indicating the more gradual curing of the sealants afterwards. It was observed that

80% or more of the 21-day sealant strength was developed within the initial 7 days period of curing.

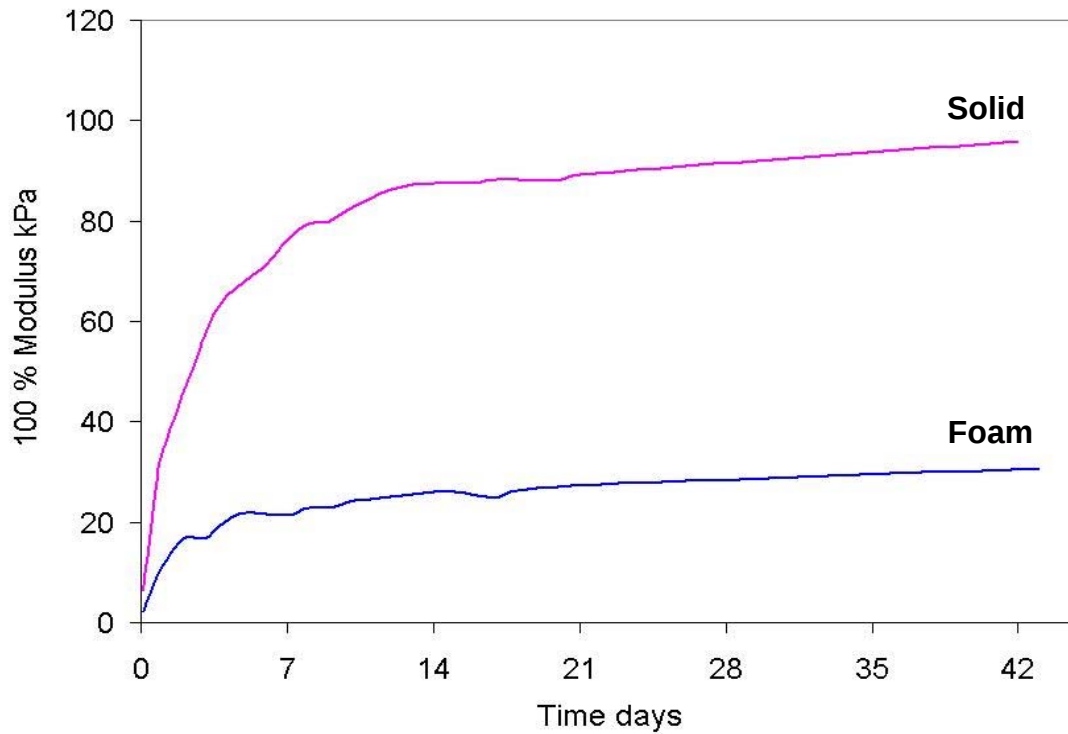


Figure 49. Curing rate of foam and solid.

Table 13. Curing Rate of Sealants

Sealant	100% Modulus, kPa				
	3 days	7 days	14 days	21 days	42 days
Foam Silicone	16.8	21.4	25.8	27.2	30.4
Solid sealant	56.9	76.3	87.5	89.1	95.9

5.11 TACK FREE TIME AND WATER TIGHTNESS TEST RESULTS

Tack free time for the foam sealant and solid sealant were found to be approximately 50-80 minutes and 30-60 minutes respectively. During Water tightness test, the non-

submerged bottom surface of each sealant was inspected for any evidence of dripping water or moisture. No sign of water leakage was detected in both sealants throughout the 96-hour test duration

5.12 RESULTS OF TESTS ON WEATHERED SEALANT

The distribution of maximum and minimum temperature to which sealants were exposed for a period of more than six months is shown in Figure 50. Similarly Fig. 51 and Fig. 52 show the precipitation and rainfall amount during the exposure. The exposure began on the 14th of December, 2004 and ended on the 28th June, 2005. The day climate data including maximum and minimum temperature, rainfall, and snowfall for the total test duration presented herein were obtained from (National Weather Service, 2005).

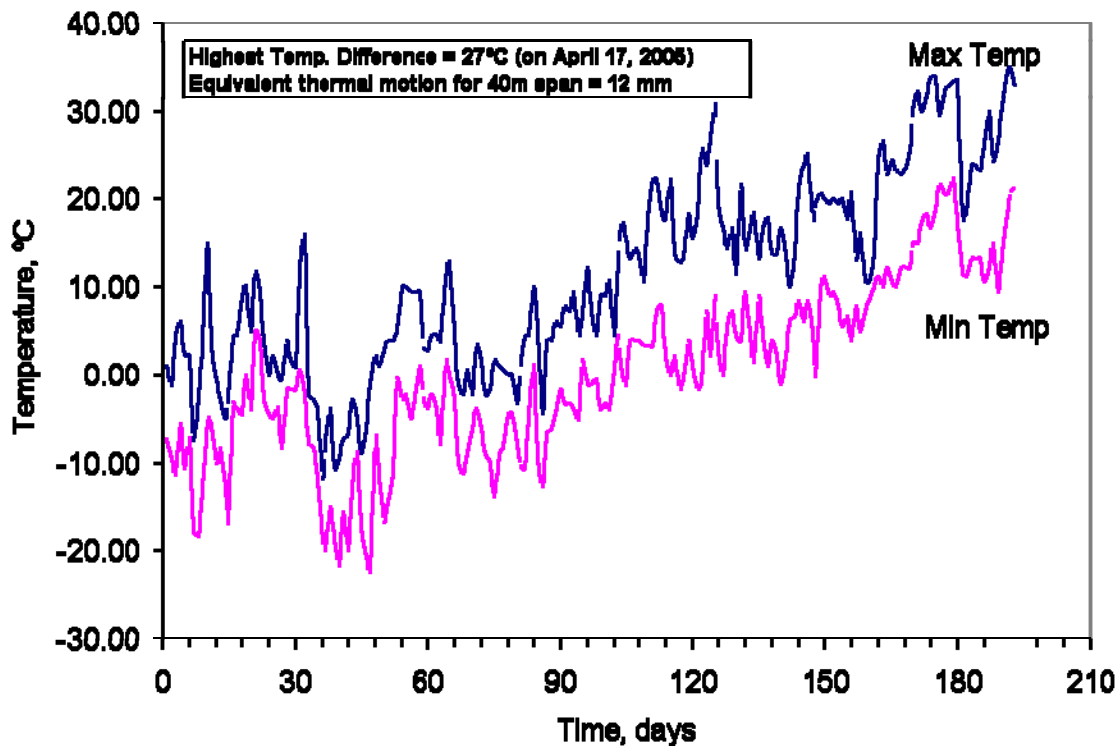


Figure 50. Maximum and minimum temperature distribution.

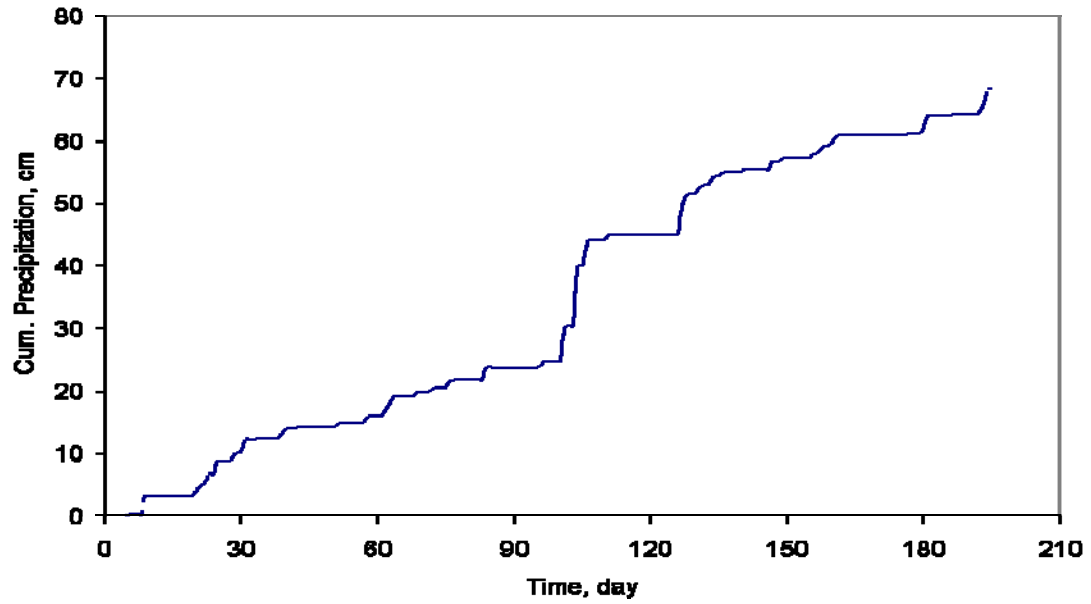


Figure 51. Cumulative precipitation.

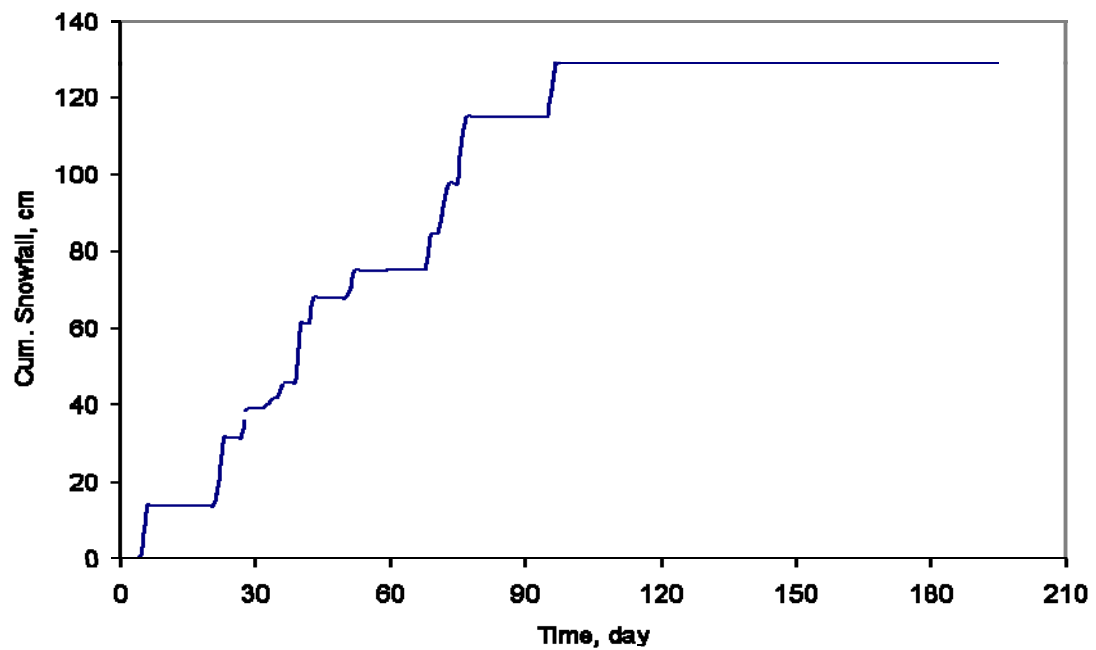


Figure 52. Cumulative snowfall.

Based on visual observation, samples were checked for crazing (fine cracks), chalking, dirt pick up, and surface erosion. Both sealants were found to exhibit none of these degradations. It should be noted that no samples were kept at dark in room condition for similar period as weathered samples to serve as the control.

5.12.1 Tension Test Result

Figure 53 is the stress-strain curve for weathered sealants. Increase in sealant stiffness at the cost of maximum percent strain reduction is observed. The 100% modulus of foam and solid sealants were measured to be 47 kPa and 101 kPa respectively. Elongations at break were 263% for foam and 344% for solid. Comparison of these results with tension test results of regular laboratory samples (3 week cured) shows increase in foam and solid stiffness by 90% and 75% respectively. Similarly, drops in elongation capacity were found to be 56% and 28% for foam and solid respectively. The observed stiffening of the sealant may be attributed to oxidation of polymers which results in loss in mechanical properties and elasticity. The continued curing reaction may have added to the stiffening of sealants by oxidation. The curing reaction normally continues at molecular level for much time even after it visually appears to be complete. The effects of oxidation and continued curing process in stiffening of sealant are however difficult to separate out as there were no control samples (kept at dark and room condition for similar period as weathered samples) to make a comparison.

Figure 54 shows the loading and unloading behavior of weathered sealants in simple tension. The strain limit was set to 200%. Only one loading and unloading cycle could be achieved for the solid sealant as a part of concrete block bonded with sealant chipped off causing tearing apart of sealant during the second cycle loading of specimen. The behavior is the same as the one observed in regular tension test described in section 6.1, only difference being that the higher level of stresses were observed this time indicating the stiffening of the sealants.

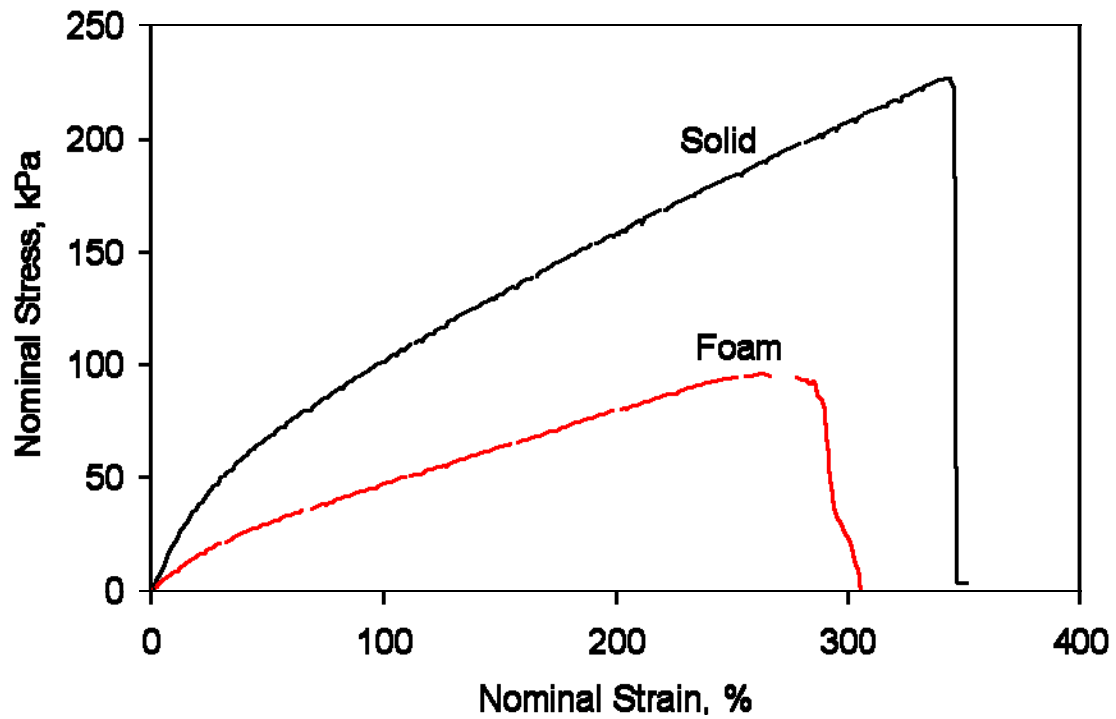


Figure 53. Tension test results: weathered sealants.

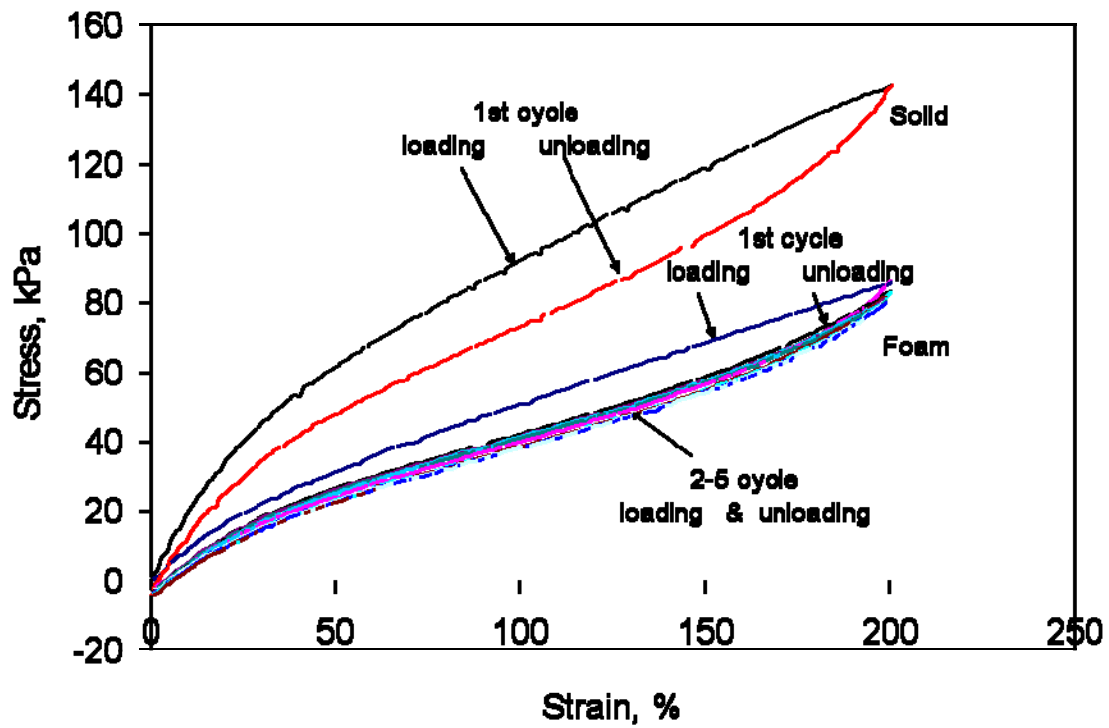


Figure 54. Tension loading and unloading of weathered sealants.

5.12.2 Shear Test Results

Results of shear test performed on weathered foam and solid sealant are presented in Fig. 55. Average elastic shear modulus of two sealants are 21 kPa and 43 kPa respectively. The corresponding values obtained for regular 2-week cured laboratory conditioned samples were 11.4 kPa and 23.4 kPa (see section 5.3). As observed in tension test of weathered samples, stiffening of sealants is observed in this case also and similar reasoning could be argued for this observed behavior.

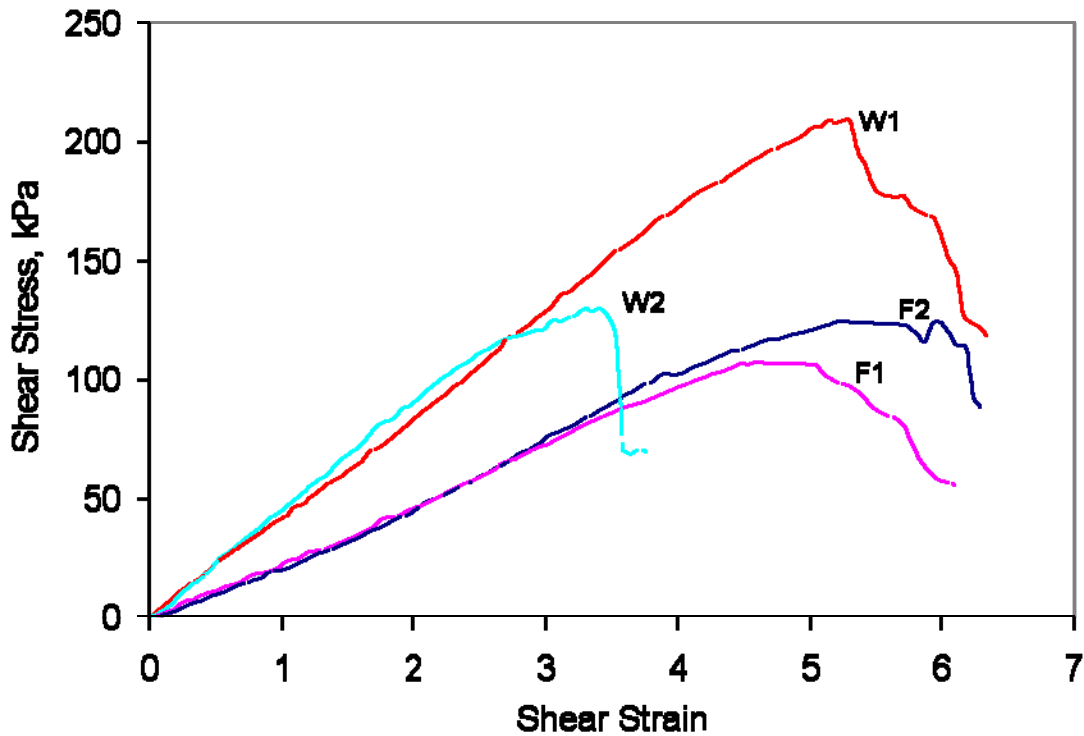


Figure 55. Shear test results of weathered sealants.

5.12.3 Stress Relaxation Test Results

Figure 56 and 57 respectively show stress relaxation test result for weathered foam and solid sealants. The decay of stress with time was recorded for 96 hour period. The total

relaxations for the foam and the solid sealants during the test period are 20% and 14% respectively (Eq. 9). A Kohlrausch-Williams-Watts stretched exponential function (Eq. 10; repeated here for simplicity) was applied to the sealant stress relaxation.

$$E(t) = (E_0 - E_\infty) \exp[-(t/\tau)^\beta] + E_\infty \quad \text{-----}(10)$$

Parameters β , E_0 , and E_∞ for foam and solid sealants are presented in Table 13. The values of relaxation constant τ in tension test are 1.5 ± 0.004 h and 1.5 ± 0.002 h for the foam and solid, respectively, where the errors are the 95% confidence limits of the values. The t-test for these two values gives a t-value of zero which indicates that the difference between these two values is not significant (critical value of t is 1.96 at $p = 0.05$). Therefore, two sealants are found to exhibit indistinguishable decay rates in tensile elongation. It was also observed that experimental relaxation curves slightly oscillate about the theoretical exponential stress decay curves.

Table 14. KWW Equation Parameters for Stress Relaxation Test: Weathered sealants

Sealant	β	E_0 , kPa	E_∞ , kPa	τ , h
Foam Silicone	0.23	51	42	1.5 ± 0.004
Solid sealant	0.24	108	92	1.5 ± 0.002

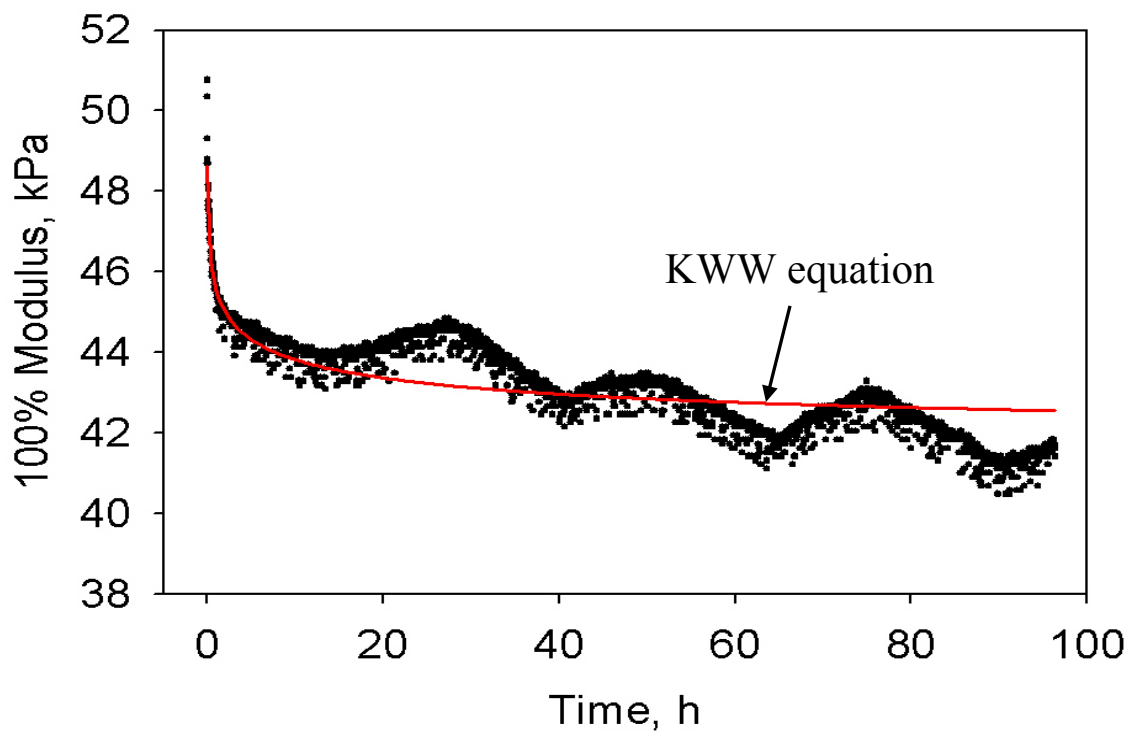


Figure 56. Isothermal stress relaxation in tension. Weathered foam sealant.

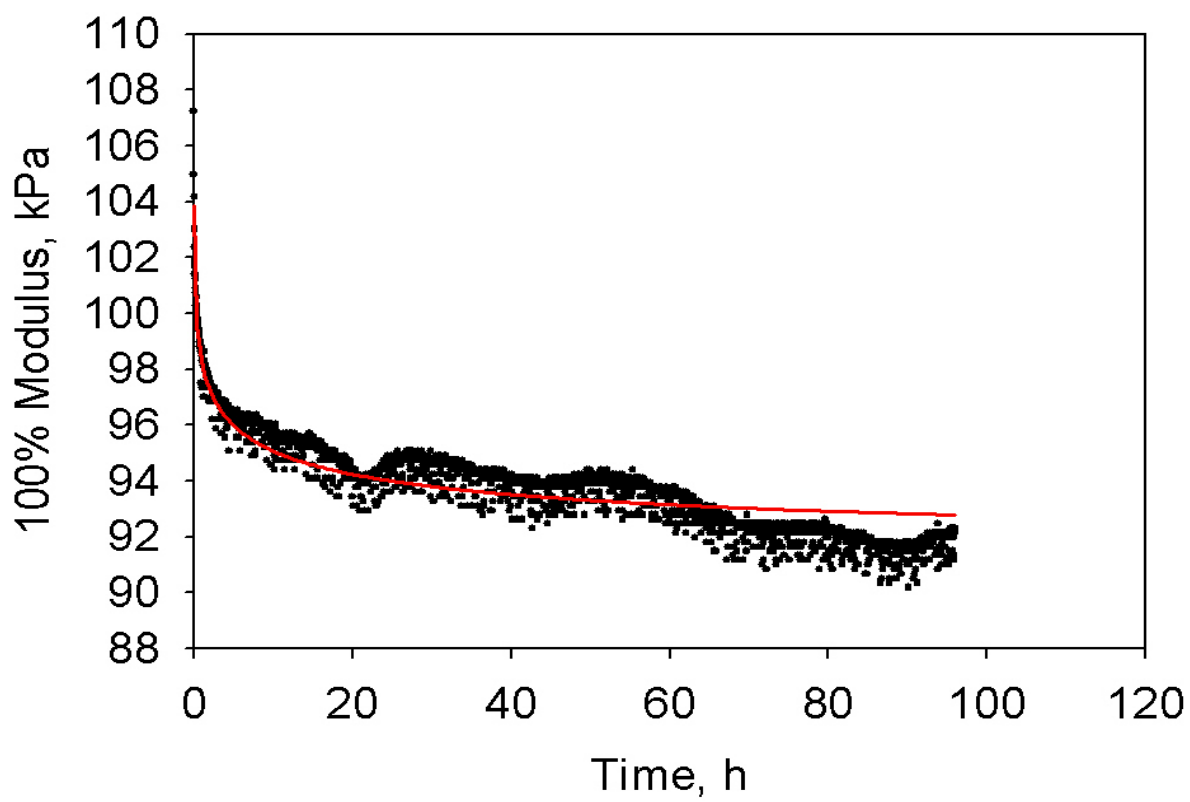


Figure 57. Isothermal stress relaxation in tension. Weathered solid sealant

6. CONCLUSIONS

The main purpose of this study was to develop and evaluate an alternate low cost and effective sealing material for small movement bridge expansion joints. A silicone foam sealant was developed in the laboratory as a potential joint sealing candidate by modifying one of the commercially available bridge joint sealants, Wabo silicone seal (Watson Bowman Acme Corp., 2003). Other commercial sealants such as Dow Corning RCS 902 (Dow Corning Corporation, 2004a) with composition similar to that of Wabo silicone seal are available in the industry. However, due to the limited resources, only one of the commercial sealants was chosen for this research. A series of laboratory tests was performed on the newly developed silicone foam sealant to evaluate its material and mechanical characteristics. In addition, for comparison purpose commercial Wabo silicone seal (solid sealant) was also assessed in the laboratory. The following conclusions can be drawn based on the results obtained from the present study:

1. The foam sealant was observed to undergo a significant rise (70%) in its volume on curing. This is a desirable feature in that it can lead to the saving in the cost of the joint sealing material and a more certain filling of cavities in the joint.
2. The foam sealant was found to have lower stiffness and greater extensibility than the solid sealant. Low modulus is desirable and is particularly important because it will help reduce cohesive and adhesive stresses developed in the seal during the joint operation.
3. When immersed in salt water solution at 45°C, the foam sealant appeared to lose its ultimate elongation capacity from 603% (dry condition) to 453% but there was no bond loss with the concrete substrate. Whereas it was observed that the salt water immersion appeared to weaken the bonding between the solid sealant and the concrete substrate

causing the sealant to pull away from the joint surface at relatively smaller average elongation value (209%) than that (475%) of its dry counterpart. It should be noted here that the sealant joints used herein for testing were prepared without the application of primers to the substrate surfaces. Primers may enhance the bonding of the foam and solid sealants with the substrate by different amount, and hence could yield different bond test results.

4. When subjected to oven aged bonding test as per ASTM D5893, no specimens were observed to develop any crack, separation, or other opening in the sealant or between the sealant and the concrete test blocks. The foam sealant was observed to be more resistant to the fatigue due to alternate cycles of cold extension and self-recompression than the solid sealant.
5. Relaxation phenomena in sealants were found to follow stretched exponential decay law. Compression relaxation times obtained for the sealants suggested that stress in foam sealant relaxes faster than that in solid sealant. For tension mode, relaxation amounts were 25% (foam) and 10% (solid) of the sealant stress at 100% extension. Corresponding statistics for relaxation in compression mode were 70% and 10% for foam and solid, respectively.
6. Creep for foam and solid after 24 hours were found to be 21% and 15%, respectively.
7. Foam sealant was observed to undergo a permanent set of nearly 20% of initial compression while solid sealant showed as little as 1.5% set. These values were observed 1 hour after the release of sealants from compression.
8. Exposure to high temperature condition increased modulus and reduced ultimate strain capacities of sealants. The oven aging appeared to assist the curing process of sealants

which became apparent in increase in measured modulus of sealants. Exposure to cold temperature condition resulted in large decrease in maximum percent elongation of foam but the final strain value thus obtained was still much higher than the required maximum in the field. The measured modulus values suggested that low temperature conditions slowed down the curing process.

9. After the freeze-thaw condition, the sealants were observed to have some decrease in maximum tensile strain percent. There was only slight effect on the sealant moduli.
10. Sealants were observed to develop nearly 64 % of 21-day curing strength within initial 3-day curing period. Also, 80 % or more of the 21-day curing strength was found to achieve by sealants within initial 7-day curing period.
11. Tack free time for both sealants was found to be less than one and a half hour, which is considered in favor of sealants as the traffic disruption time will be minimal during joint sealing operation.
12. None of the sealants showed any sign of water leakage during the water tightness test.
13. No significant deterioration was observed in the sealants (cracking, surface erosion etc.) subjected to weathering effects for 6 and one-half month period. Laboratory tests suggested higher stiffness after subjecting to weathering. Tension test showed the drop in elongation at break. The increased stiffness and decrease in elongation might be attributed to the oxidation of polymer and continued process of curing of sealants.
14. From the stress relaxation test of the weathered sealants, both foam and solid sealants were found to exhibit similar decay rate in tensile elongation. The experimental relaxation curves are observed to slightly oscillate about the theoretical exponential stress decay curves.

7. RECOMMENDATIONS FOR FIELD DEMONSTRATION AND MONITORING (PHASE II)

7.1 RECOMMENDATIONS TO PROCEED TO PHASE II

The results of laboratory tests performed so far on newly developed foam sealant are very promising of its successful performance as an economic and effective bridge joint sealant material. The rise in the foam volume once the curing reaction is complete can lead to a significant economy in the bridge joint sealant operation while its low modulus nature will prevent excessive interfacial stresses from being developed at the sealant substrate interface thus helping the bond between the sealant and the joint surface to remain intact during the opening of the joint. Debonding of the sealant from joint substrate has been reported as one of the major problems associated with commercially available silicone sealant. Various laboratory tests including salt water immersion test results have indicated the better bonding properties of foam sealant compared to the solid sealant. Besides above, foam sealant's rapid curing, easy to install, self-leveling, and low modulus properties make it a very suitable candidate for joint sealing operation. It is strongly recommended that the sealant material be tested in the field by installing the joint seal in a real bridge and its performance be monitored continuously. Therefore, it is concluded that Phase II of this project work is highly warranted and the research teams strongly recommends for the implementation of Demonstration and Monitoring Phase (Phase II).

7. 2 RECOMMENDED MAJOR TASKS FOR PHASE II

The major tasks recommended for Phase II of the project are presented below. The tasks are grouped under 3 categories (a) Pre-Field Installation, (b) Field Installation, and (c) Post-Field Installation and Monitoring.

7.2.1 Pre-Field Installation Tasks

1. It is important to have sealant performance evaluated under cyclic loading as the bridge joint is constantly subjected to dynamic loading due to vehicular traffic. Deflection controlled cyclic loading test should be performed in laboratory to simulate dynamic deflection of joint sealants, namely normal deflection due to temperature and shear deflection due to wheel loads.
2. The sealant bonding tests so far were done with the concrete substrate. Since concrete surfaces have irregularities and the sealants normally stick better with these rough surfaces. Therefore, adhesion/bonding tests to steel should be done in the extension.
3. Foams sealant developed in this study seems to give better results than the solid sealant without the primers. However, more investigation is needed to compare the bonding performance between these two sealants in the presence of primers.
4. In order to eliminate the possibility of air gain and loss by foam sealant during stress relaxation in tension and compression modes, it is recommended that the relaxation test be performed in shear mode. Dynamic Mechanical Analyzer (DMA) machine is capable of performing the relaxation test in shear using the sandwich arrangement.

5. Since the concrete and steel will be the most frequently encountered joint substrate material in new construction and repair works, water tightness of sealant should be tested on specimens bonded to these substrate materials.
6. Puncture test of sealant is essential to evaluate its ability to withstand debris forced into the joint by moving traffic. Poking objects or devices of various shapes can be pressed against the sealant with appropriate load magnitudes to see the occurrence of any damage to the sealant.
7. Effects of humidity on the behavior of the foam sealants had not been evaluated in this first phase of the project. This should be evaluated in Phase II of the project.
8. So far, small batches of foam sealant have been produced in the laboratory to prepare test specimens of small dimensions (e.g. 0.5” length/width and 0.5” thickness). Hence, for the field installation purpose, a larger volume of the sealant needs to be prepared and applied to joints of larger dimensions as found in real bridges. The quality and basic behavior of the sealant materials thus prepared and applied should be assessed.
9. A proper sealant dispensing tool should be designed to facilitate the effective mixing of foam sealant components and its easy installation in the bridge joints in the field. An applicator gun should be designed such that it will be able to hold and produce sufficient sealant volume to facilitate the quick joint sealing operation.
10. It is essential that the sealant component mixing and joint sealing operation be conducted in the ambient field outside laboratory environments before proceeding to the real bridge application. These operations can be done in prototype joints between 2 concrete blocks or two steel beams outdoor in the field environment. This will give confidence in the

preparation of joints, sealant pouring and mixing and joint installation, in general. A suitable method of vertical joint sealing method should also be established.

7.2.2 Field Installation Tasks

It is envisioned that the field installation procedure for the foam sealant can be similar to that used for the 2-part, cold applied silicone sealants currently in use for bridge expansion joint sealing (for example Watson Bowman Acme Corp., 2003; and Dow Corning Corp, 2004b). The tasks for the field installation of the sealant thus include, but not limited to, the following:

1. Selection of bridge(s): Selection of one or more candidate bridges for the joint installation and monitoring should be accomplished in coordination with NETC project Technical Committee members who come from the transportation agencies of each of the six states in the New England region. For the first application and demonstration of the sealant, a low traffic volume bridge with expansion joint needing repair should be selected. It is also recommended that the sealant be applied only to a couple of feet length of joint first and its performance be monitored and evaluated for some extended duration, before applying the sealant to the whole width of the bridge cross-section.
2. Joint preparation: The joint interface must be free of dirt, coatings, oil, grease, rust and other contaminants. For this purpose, sand blasting is recommended. Air blasting of the joint after sandblasting is necessary to remove all debris in the joint and surrounding area. To insure cleanliness of each joint interface should be wiped with a clean rag.

3. **Backer Rod:** A backer rod is required to prevent the flow of the sealant through the joint during joint sealing operation and to ensure the proper shape and depth of the sealant reservoir. A closed-cell, expanded polyethylene foam rod with approximately 25% larger in diameter than the joint gap is recommended.
4. **Mixing of Sealant Components:** Sealant components should be applied using proper dispensing equipment. They should be mixed thoroughly and applied at the weather condition (room temperature $\sim 23^{\circ}\text{C}$ and dry) when they produce the most effective joint sealing characteristics.
5. **Application of Foam Sealant:** The foam sealant begins to rise in volume once it is poured in the joint during the initial curing period. Therefore, the amount (depth) of sealant to be poured into the joint must be carefully monitored so that when it is fully installed, some recess from the riding surface is maintained to prevent the direct contact of sealant to the vehicle tires.
6. **Traffic control during joint preparation and installation:** The tack free time of foam sealant is approximately 50-80 minutes. Traffic closing and reopening should be appropriately monitored.

7.2.3 Post- Field Installation and Monitoring Tasks:

A variety of tasks, including monitoring and inspection of the joint sealant, are recommended after the sealant is installed in the bridge joints. They include, but not limited to, the following:

1. Regular visual inspection/monitoring for any cracks, separation of sealant from the joint substrate, and damage due to debris.

2. Continuous recording of joint movement – amount of opening and closing
3. Continuous recording of temperature
4. Recording of weather elements, rain-fall, snow fall, and extreme weather events, such as hurricane, flooding, etc.
5. Traffic data recording – traffic volume, speed, vehicle types, loads, etc.

Some special instrumentation might have to be installed to monitor and record data as noted above, such as joint opening and closing and traffic data.

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