THE TENSILE PERFORMANCE OF
CLOSED CELL FOAM EXPANSION JOINTS:
A STUDY ON THE DELETERIOUS EFFECTS OF
COMPRESSION SET

by

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ABSTRACT

Closed cell foam is a polyethylene based foam that is used as a gland material for a specific type of bridge deck expansion joint, usually in applications where the total movement to be accommodated is four inches or less. Adhered into the gap of an expansion joint, this material is responsible for maintaining a water tight smooth transition between deck slabs, and for preventing the infiltration of corrosive agents through deck runoff. While currently a viable option for small movement applications, some state agencies have begun shying away from these foams, as reported failures in tension have caused its reliability to become suspect. In determining the cause of these tensile failures, the permanent loss in thickness due to load cycling, also known as compression set, was thought to be a likely contributor. This loss of elasticity will cause unanticipated stresses in tension that could in turn cause failure of the joint, either by tearing of the foam, or a loss of bond with the gap wall. To investigate the possible correlation between compression set and the tensile failure of closed cell foams, the current methods for determining compression set had to first be evaluated, followed by a series of tensile tests that investigated the involvement of compression set in tensile performance.

A series of compression tests were conducted in accordance with the current ASTM standard for measuring compression set. This test is conducted at ambient temperature (73°F) and for a compression cycle duration of just 22 hours. A parallel set of experiments were also conducted to simulate the actual in-service conditions of a bridge joint. This involved holding the specimens compressed for up to 3 months, at both ambient (73°F) and elevated temperatures (110°F). It was discovered that the current standard is likely to produce values of compression set that are significantly

inaccurate when considering the lengthy periods of compression and recovery, and elevated temperatures, that these products are likely to experience in actual bridge joints. The results showed that compared to the 9-10% compression set typically reported by manufacturers who test in accordance with the current standard, foam samples exposed to more realistic compression cycles and rebound periods exhibit only half as much compression set (4-5%) at ambient temperatures (73°F), and more than three times as much (30-35%) at elevated temperatures (110°F). Modifications to the duration and testing temperature of the current standard may be necessary for the test to yield results that are appropriate for the bridge joint application.

A series of tension tests were also conducted on specimens subjected to various amounts of compression set, to determine the presence and magnitude of any correlation between compression set and tensile performance. The foam specimens were bonded to steel plates using the manufacturer's adhesive, subjected to 24 hour and 1 month compression cycles, and loaded in a tension testing machine to failure. The results of these tests showed that for every specimen tested, the elongation at failure was far greater than what is reported by the foam manufacturer, implying a positive tensile performance even in the presence of compression set. All specimens experienced 70-110% elongation in tension, which is much greater than the 20-30% reported by manufacturers. The direct conclusion of these tests is that compression set is not the sole cause of poor tensile performance of closed cell foams. However, these results were entirely contingent on a scrupulous adherence to the installation procedures provided by the manufacturer. Several small instances of negligence during assembly of the bonded specimens had significant detrimental effects on the tensile performance of the foam, implying that improper installation is a more likely cause for limited tensile capacity of closed cell foams. Especially when dealing with the adhesives, diligence in proper installation techniques is essential in creating a strong bond and a high quality joint.

Chapter 1

INTRODUCTION

1.1 Background

1.1.1 Small Movement Expansion Joints

A small movement expansion joint (SMEJ) in the application of bridge design can be defined as a device that allows for the thermal expansion of the bridge deck. Almost all bridges require a gap (or joint) in the deck between interior spans or between the exterior spans and the approach roadway, in order to avoid the unnecessary accumulation of thermal stresses that occur because of changes in temperature during the day, and on average with the change in seasons. Small movement in this case, is defined as a maximum of 4 inches. These devices usually consist of a header (steel or elastomeric concrete) that is installed into the deck material and lines the outside of the joint, and a gland that is attached to the face of the header to fill the joint, usually consisting of an elastomeric material (Figure 1.1). In addition to maintaining a smooth transition over these necessary gaps, SMEJs also prevent the infiltration of water and other chemicals to the materials of the superstructure. Without a properly functioning SMEJ in place, these chemicals, such as deicing fluids, will seep down onto the structural components below, causing corrosion of steel and spalling of concrete. The proper installation and maintenance of these devices is vital for the life-cycle of the bridge and the avoidance of significant damage to the associated structural elements.

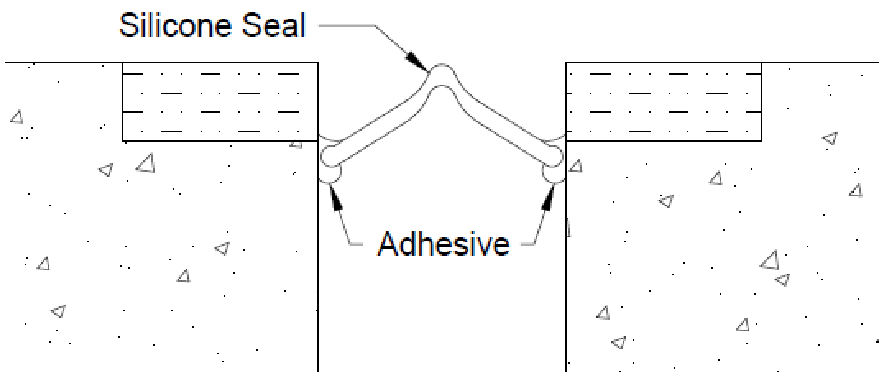


Figure 1.1 Typical SMEJ Cross Section (Preformed Silicone)

1.1.2 NCHRP 12-100

Though an important element in the bridge deck system, there is a surprising lack of formal guidance on the maintenance of SMEJs. There are no national guidelines or specifications, so state agencies often create their own "in-house" specifications, based only on their individual experience with certain varieties of SMEJs and supplier recommendations. In light of this need for a cohesive document, the NCHRP research project 12-100, "Guidelines for Maintaining Small Movement Bridge Expansion Joints", was created to explore the current practice of SMEJ maintenance and synthesize national guidelines. These guidelines are to include joint failure mechanisms, performance metrics for the different varieties of SMEJs, and procedures for the maintenance, repair, and replacement of SMEJs. The information synthesized was to be collected from a multitude of sources, including a literature search on all existing SMEJ maintenance documentation, and an electronic survey administered to a variety of bridge stakeholders including owners, consultants, suppliers, and contractors. In addition to this research, there were a number of other investigations performed to support the synthesis of this information, particularly pertaining to a number of issues that affect the long-term performance of SMEJs that are not currently well understood. These issues include the lack of standardized testing for SMEJ material properties, the lack of life cycle cost data for bridge joints, and the elastic phenomenon known as compression set, which occurs most commonly in closed cell foams. The efforts to investigate compression set in closed cell foams is the focus of this study, the information from which will ultimately be utilized in the support of the larger NCHRP project.

1.1.3 Compression Set

The term compression set describes the permanent deformation that remains in a material after a stress that was previously applied is removed (Figure 1.2). This loss of elastic properties is quantified as the percent of the original thickness lost after the stress is removed and it rebounds to its new thickness. Due to their relatively low Young's modulus, elastomers such as closed cell foams are particularly susceptible to this phenomenon.

Figure 1.2 Compression Set in Bridge Parapet Joint Gland

1.1.4 Closed Cell Foam

The SMEJ gland material known as Closed Cell Foam (CCF) is a low density cross linked polyethylene foam, which is adhered to the walls of the header material by a two part epoxy adhesive in order to create a watertight seal as shown in Figure 1.3. The specific chemical make-up of each foam product varies by supplier, but they all achieve the same function, and are recommended for the small movement ranges investigated by this study. This specific variety of SMEJ is of particular interest to this study because of its susceptibility to the phenomenon of compression set. Though many manufacturers of CCFs report an acceptable extension of 20-30% in tension, reported failures of CCFs related to bond failure or foam tearing in tension have led some owners to grow cautious of this device’s tensile capacities (Milner and Shenton, 2014). Peter Weykamp, former Bridge Maintenance Program Engineer for the New York State DOT, noted this poor performance of CCFs in tension over his 16 years of developing maintenance programs for an inventory of over 8,000 bridges. His collaboration with other bridge owning state agencies verified that this problem with CCFs occurs in a variety of states throughout the country (Weykamp, 2014). One possibility is that the relatively poorly understood effects of compression set could be contributing to the reported tensile failures. The validity of this claim, and the response of CCFs influenced by the effects of compression set in compression and tension are the primary investigation of this study.

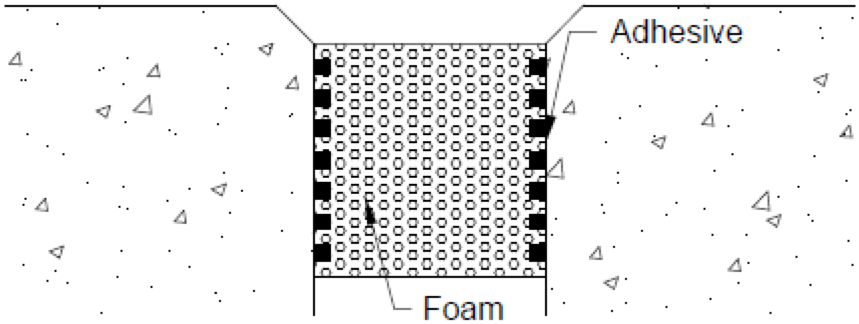


Figure 1.3 Typical CCF Cross Section

1.2 Statement of Problem

The material that comprises the gland of a SMEJ is often subjected to conditions that generate compression set, which can lead to a direct failure of the material and consequently the entire joint. When a bridge deck experiences elongation in the heat of the summer months, the material in the seal is compressed to its maximum. As the bridge cools and shrinks, the material will be expected to rebound in concert with the deck and return to its original thickness. With the onset of compression set during this rebound cycle, any permanent deformation that inhibits the material from fully expanding will put stress on the seal and bond, either of which may fail under the unanticipated tensile stress.

In order to combat this, most manufacturers will report the compression set values of their material that the designer can consider while selecting a joint type and determining its size. In the case of CCFs, the most commonly referenced standard for compression set testing is ASTM D3575, which requires a 22-hour compression cycle. As the season dependent compression cycles that these materials experience in service are on the order of months, it is immediately apparent that this testing standard may not be appropriate for the bridge application, as the cycle required by ASTM D3575 is only a small fraction of what the material will actually experience in a bridge joint. In addition, the material is to be compressed at an air temperature of 73° F, which is a significant 20° to 30° cooler than the average daily temperature that portions of our country experience during the summer months when the material is being compressed to its maximum. For these reasons, the appropriateness of this testing standard has come into question. This study endeavors to evaluate the accuracy of this test as it applies to in-service expansion joint seals. Through performing the traditional test alongside modified trials that better simulate in-service compression cycles and temperatures, the contrast of these results will reveal any inconsistencies in the current standard and suggest modifications to improve its suitability.

1.3 Literature Review

A literature search was conducted to investigate the existing research on CCFs. Due to a number of beneficial thermal and elastic properties, CCFs have a significant presence in insulation and cushioning applications. There was a significant amount of literature discovered involving these two applications, but an exhaustive account of these studies was not the intent of this investigation. Instead, a select few studies were chosen that were found to accurately represent the majority of the most commonly researched topics. Of the two main applications, the following topics are covered in the selected reports: thermal expansion coefficient, thermal diffusivity and specific heat capacity, long-term thermal performance and aging, micro-structural mechanics, and dynamic cushioning performance. It is important to note that when the search was limited to CCFs and their application in expansion joints, the results were very limited. Very few studies acknowledge this application, and only one study was discovered to focus specifically on this use of CCFs. This study is also included below, and involves the performance of CCFs through weathering such as UV radiation and salt water submersion, conditions CCFs are likely to experience as bridge joint glands.

Thermal Expansion Coefficient and Bulk Modulus of Polyethylene Closed-Cell Foams (Almanza, et al 2004a), seeks to determine the accuracy of a currently accepted theoretical model for calculating the thermal expansion coefficient of polyethylene foams by comparing its results with experimental data. The report begins by introducing the Kelvin model, an accepted representation of a polyethylene foam that assumes a tetrakaidecahedral lattice structure. An important aspect of this model, the author points out, is that the cell faces begin and remain flat during loading. The mechanics of this model are then explored in detail, citing the theoretical equations for the foams relative density, bulk modulus, and thermal expansion coefficient, among other properties. The accuracy of the theoretical equations presented by this model are then evaluated by a series of experimental tests conducted by the authors. A particular variety of polyethylene foam is selected for testing for multiple reasons, including nearly isotropic cellular shapes. Density, cellular structure, isotropy, and many other parameters were determined in the testing, with the test methods described briefly for each. When comparing the experimental data with theory, it is discovered that the experimental values for bulk modulus are much lower than the theory would suggest. Since the equation for the coefficient of thermal expansion is a function of the bulk modulus, applying the theoretical value would yield inaccurate results. However, it can be shown that applying the experimental value of bulk modulus to the Kelvin model's equation for the coefficient of thermal expansion, yields reasonable values of this coefficient when comparing them to the experimental results.

A second study conducted by Almanza in 2004 (Almanza, et al 2004b), *Measurement of Thermal Diffusivity and Specific Heat Capacity of Polyethylene Foams Using the Transient Plane Source Theory*, describes the construction of a theoretical model used to predict thermal diffusivity in polyethylene foams. The data used in this model was collected from an experiment in which the transient plane source method was employed to determine the thermal conductivity, diffusivity, and capacity of a polyethylene foam specimen. The theory for the model is explored, beginning with the fundamental equation for heat conduction of a homogeneous isotropic solid, and continuing onto the equations for conductivity, diffusivity, etc. The experimental set up is explained, which consists of a hot plate sensor placed between two blocks of foam. In this set up, the plate acts both as the sensor, and the heat source. In analyzing the data, an almost perfect linear relationship is discovered between heat capacity and density of the foam. The thermal diffusivity also showed strong correlation to the inverse of foam density. Both of these trends were compared to the theory of the presented model, and good overall agreement was determined.

Closed Cell Foam Insulation: A Review of Long Term Thermal Performance Research (Stovall, 2012), investigates the existing research on thermal performance of closed cell plastics, the science of aging and the test methods that have been developed to address it, and the models that are available to predict long term performance. While this report contains an exhaustive list of other relevant studies in its appendix, one study, *The Physics of Heat Transport Through Closed-Cell Foam Insulation* (Glicksman, 1994), is covered in detail as the comprehensive resource for this topic. The main topics from this study are covered, and five fundamental equations are included to support these topics. The author takes a similar approach to the topic of aging, covering *The Science of Foam Aging*, by Hoogendoorn (Hoogendoorn, 1994), as the authority for this topic. The fundamental equation for aging is presented, and an example plot of time/thickness^2 vs. thermal conductivity is provided. The author then claims, citing several reasons, that accelerating the aging process is desirable. Three of the most popular testing methods for accelerating the aging process of closed cell foams are discussed, including elevated temperature, thin slicing, and measuring diffusion rates to facilitate models. A number of models are also investigated, including models presented by the National Research Council of Canada, Massachusetts Institute of Technology, and other scholarly works. Most rely on the analogy between heat and mass transfer to calculate gas diffusion coefficients, developing further levels of sophistication based on the requirements of the model.

The first of the studies related to CCF in cushioning applications, *The Mechanics of Three-Dimensional Cellular Materials* (Gibson, 1981), describes a study conducted to better understand the microstructural mechanics of cellular materials such as open-cell flexible polyurethane, closed-cell rigid polyurethane, and closed-cell flexible polyethylene (the specific variety of foam used in most expansion joint products). Basic established mechanics and existing literary works are first discussed, which provide tables and charts of foam material properties, microstructural images, and idealized stress-strain curves. Next, a dimensional analysis is performed to demonstrate the relationship between the properties of the foam as a whole, and the properties of the individual microstructural cells. Further theoretical analysis is extrapolated from traditional mechanics, including linear and nonlinear elastic behavior, plastic behavior, and contributions of individual cellular elements to stiffness and strength. The study then performs a refinement of the above analysis, demonstrating the short comings of traditional mechanics in this context, and using other relevant scholarly works to improve the calculations of the following: relative density, elastic moduli by including the shear and axial contributions to deformation, nonlinear elastic behavior, and plastic collapse. A range of validity for these new equations is also discussed. In the final analysis, the theoretical equations presented in this study are verified against existing experimental data. Most of the refined analysis is concurrent with the experimental data, with the exception of some of the closed-cell specimens. It is observed that closed-cell specimens tend to behave more like open-cell specimens in theory, which is believed to be caused by most of the material in each cell concentrating in the edges during fabrication.

Initial Impact Studies on Open and Closed-Cell Foams (Sims, 1997), investigates the dynamic cushioning performance of open and closed cell foams. Four varieties of foam were selected for testing, including a closed cell polyethylene, and an open cell polyester, polyether, and polyurethane. The main investigation was to observe the deceleration that the foams could provide on impacting objects, and determine the micro-structural properties of each type of foam that dictate its behavior. Two types of samples were prepared from each variety of foam: an unvoided sample, and a voided sample. The unvoided samples were 150 x 150 x 50 mm solid cuboids, while the voided samples were created by removing centrally placed square voids (of varying sizes) from the solid. The experimental set up consisted of an accelerometer attached to a drop hammer, which would be allowed to fall on a foam sample which rested on a rigid surface and a pressure transducer. Results recorded included peak G vs. hammer weight, deceleration vs. time, pressure vs. time, and peak G vs. void size. From the readings of the pressure transducer during testing, it was shown that the principal damping agent in closed-cell foams is gas compression, while open-cell foams rely on gas flow and pressurization in the early portions of the impact cycle, followed after by gas compression. These readings were verified by the voided samples. Little difference was found between voided and unvoided closed cell samples. This is believed to be a result of the "cell" that is formed by the void encapsulated by the rigid surface and the drop weight. Though infinitely larger than its microscopic counterparts, this cell works much in the same way, gaining most of its damping capabilities from gas compression. For open-cell foams, voided samples exhibited a significant change in performance, unless the void size was significantly small. This agrees with the conclusions drawn from the pressure data, which suggests that the damping comes mostly from the gas flow and pressurization, and only later from gas compression.

The only study to report on the application of CCFs in bridge joints, *Effects of ultraviolet radiation on morphology and thermo-mechanical properties of shape memory polymer based syntactic foam* (Xu, et al 2011), investigates the performance of closed cell expansion joint foam when exposed to environmental conditions such as UV radiation and water immersion. The chemical composition of such foams are presented in detail, and many other studies are cited to demonstrate why this composition is particularly susceptible to UV radiation. Several foam samples were created specifically for this test, and were subjected to a thermo-mechanical cycle known as programming, in order to render the foam "smart". To observe the synergistic effects of UV radiation and water immersion, groups of specimens were submerged in fresh water, some in salt water, and some control groups were not submerged at all. All specimens were then subjected to direct UV radiation for 90 days, before being placed through a series of compression, tension, and recovery stress tests. The compression and tension tests were conducted at room temperature and strained to 40% of their original length, while the recovery test restrained the ends of the specimen and brought it to 90° C, monitoring the resulting thermal recovery stresses. All samples portrayed a yellowing characteristic that increased linearly with the duration of exposure, and tiny cracks were discovered near the surface that were believed to be caused by the combination of the programming and UV exposure. The results of the compression test show a slight decrease in compressive strength, and a slight increase in elastic modulus. This loss in ductility is believed to be caused by the surface cracking mentioned above, and is investigated on a microscopic level. The results for the tension tests were very similar, each showing a decrease in tensile strength and extension at failure, but an increased modulus. The samples that were submerged in water saw a general decrease in compressive and tensile strength, with the members submerged in freshwater seeing a greater decrease then those in saltwater. The results of the recovery stress test produced compressive stress values for the samples in the following order, from greatest to least: control group, UV sample, UV and saltwater sample, and UV and freshwater sample. Though all of the above samples saw some form of loss in mechanical properties, this study deemed the reported losses in performance were not great enough to inhibit the shape recovery properties of the foam, and that such materials will still be able to perform well in such environments.

Additional reports and papers were reviewed in support of the NCHRP 12-100 project, mainly investigating the current status of SMEJ maintenance on a broader scale. Many of these works evaluate the performance of specific joint types, and a few contain research on CCFs specifically. The NCHRP Synthesis of Highway Practice 141 (Burke, 1989), and 319 (Purvis, 2003) reports were written with common goals in mind: to identify the most commonly utilized joints, identify their individual strengths and common issues, and improve the general state of practice. Both reports identify the various applications and advantages of CCFs, among other common joint types. Common issues with CCFs were also identified, but no objective research was performed to determine the cause of these performance problems. General design considerations and recommendations for improving the lifespan of SMEJs were provided, but very little of this advice applies directly to CCFs. Among other studies with similar scopes, the PennDOT study “Bridge Deck Expansion Joints”, (Dahir and Mellott, 1987), also includes an evaluation of the most common bridge joints in use, in the state of Pennsylvania. This particular report assigned an objective performance value to each in-service joint based on the following parameters: general appearance, condition of anchorage, debris accumulation, watertightness, surface damage, noise under traffic, and need for maintenance. These parameters were rated on a 0-5 scale, and the total averages were then weighted according to the significance of the parameter. While this study does contain a fairly detailed and objective analysis of the performance of bridge joints, there is no investigation into the cause of any poor performance, and as such, specific phenomena like compression set are not mentioned.

1.4 Objectives

The primary objective of this study was to investigate the effect of compression set on CCFs, and evaluate the accuracy of the current ASTM standard as it applies to the compression set experienced by in-service CCFs used in bridge joints. By conducting a series of tests performed in accordance with the current ASTM, alongside parallel tests conducted at elevated temperatures and for longer compression cycles, a comparison was made to observe the validity of the more idealized ASTM standard. A follow-up study was then conducted on the same samples, which continued to measure their final thickness (and therefore their compression set) long after the recommended 24-hour rebound period. This was in an effort to evaluate the rebound period suggested by the ASTM standard, which is also far less than what bridge joints experience while in service.

One additional series of tests that were conducted involved performing tensile capacity tests on adhered samples that have experienced a compression cycle, in order to simulate the tension that a CCF joint will experience in the colder months due to the contraction of the bridge deck. This series of tests was performed to determine the tensile capacity of the foam as well as the strength of the bond, in order to better understand the more realistic repercussions of compression set. If the foam or adhesive were to fail when the foam section was still near its original thickness, or within the prescribed tensile limits (usually 20-30% of the original thickness), it would suggest that the effects of compression set are making a significant contribution to the failure of these foams. If neither the foam nor adhesive fail until the extension of the foam has far surpassed its original thickness, this would suggest that the existence of compression set in a foam member may not be significantly affecting its tensile capacity at all. This test will be the final step in better understanding the effects of compression set on CCFs, and the validity of the current testing standards that govern their behavior.

1.5 Organization of Thesis

The remaining three chapters of this document include two chapters that discuss the experiments of this study in detail, and one conclusive chapter that consolidates all of the relevant findings. Chapter 2 covers all of the compression tests, while Chapter 3 covers the tension tests. Both of these chapters are organized in the same fashion: introduction, test set-up and procedure, and results and discussion. The introduction reestablishes the goals of the experiment, defines the scope, and states the significance of the targeted findings. The test set-up and procedure section describes in detail the process of preparing the specimens for testing, and the significance of the preparation methods as they apply to the reliability of the anticipated results. The results and discussion concludes the chapter by presenting the data collected in a fashion that facilitates the analysis of data trends and the comparison of results from trials with contrasting testing conditions. This information is then used to verify, reject, or further explore the claims presented in the goals of the experiment. The final chapter, Chapter 4, aims to reiterate the motivation for the study as a whole, and explain why each experiment was selected and what was hoped to be learned from each. The relevant findings from each study were summarized and combined to comment on the findings of the study as a whole.

Chapter 2

COMPRESSION TESTING

2.1 Introduction

The current ASTM standard for determining the compression set of CCFs (ASTM D3575-14, see Appendix A) involves creating foam testing specimens by cutting a standard CCF roll into slices, and compressing these specimens to half of their original thickness. These compression cycles last for 22 hours and are conducted at room temperature. The specimens are then allowed a rebound period of 24 hours, after which the thickness is measured and the compression set is calculated. The validity of this standard however, for bridge joint applications, has come into question. The duration of the suggested compression cycles and the prescribed use of room temperature both vary significantly from the environmental conditions that CCFs will experience in a bridge joint. In this study a series of experiments were conducted to evaluate the accuracy of this standard by modifying the temperature and compression cycle duration for a portion of the specimens, and comparing these results with those produced by the standard procedure. In order to ensure that these were the only two parameters being investigated, a strict adherence to the standard procedure in all other facets was ensured. In addition, to ensure the validity of these findings could be verified, these experiments were conducted using CCFs from four different suppliers: Watson Bowman Acme, Chase, Polyset, and R J Watson.

At the conclusion of the compression tests, the analysis of the data raised questions about the validity of the prescribed rebound duration. In an effort to address these questions, a series of follow-up tests were conducted on the same specimens in an effort to isolate and evaluate the rebound duration parameter from the current standard. Just as the compression cycle duration was suspected to be unrealistic, the prescribed amount of time allotted for the specimen to rebound before final thickness measurements are taken seemed inadequate. Thickness measurements for longer rebound periods were collected for all samples and compared with their standard counterparts.

Presented below are the necessary preparatory steps and results of the experiments designed to evaluate the appropriateness of the compression cycle, testing temperature, and rebound period prescribed by ASTM D3575 as it applies to SMEJs. The strict adherence to the standard's other procedures will be verified through a detailed description of the experiments test set-up and procedure. The resulting compression set values will be presented for comparison with values typically reported by manufacturers, and plots of compression set versus rebound period will provide insight into the necessity of modifications to the current standard.

2.2 Test Set-Up and Procedure

2.2.1 Compression Tests

Preparing the foam specimens in accordance with the current standard was the first step in the test procedure. The standard requires a minimum of three replicates to be tested per material, in order to minimize the presence of outliers and verify the validity of the findings. The dimensions of each replicate are required to have a cross section of 2" by 2", and a thickness of 1". Assuming that the material is isotropic, it was ordered from each supplier in 2" by 2" by 36" rolls and cut into 1" slices using a horizontal band saw (Figure 2.1), such that the cross section of each specimen was the same. A labelling system was implemented to keep the specimens organized, which consisted of three characters that were inscribed on one face of each specimen. The first character represented the temperature of the test ("R" or "E" for "Room" or "Elevated" temperature), the second represented the duration of the compression cycle (in number of months), and the third represented the replicate number (1, 2, or 3), as seen in Figure 2.1. The first initial of the supplier was also labeled on a separate face in case the difference in color and design was not enough to distinguish between the products.

Figure 2.1 Band Saw and Foam Roll (left and center); Specimen Labelling System (right)

The apparatus that was required to compress the specimens was described in the standard as two steel or aluminum plates held together by bolts or clamps, with a deflection thickness that is controlled by spacers. The only requirement for the dimensions of the plates is that they are of sufficient thickness to prevent deformation of the plate during compression. In order to accommodate 12 specimens per apparatus (4 suppliers by 3 replicates), it was determined that 12" by 12" by 3/8" aluminum plates would provide sufficient thickness and surface area. The size was controlled by the standard's requirement that the compressed specimens must not come into contact with each other at any point during the compression cycle. The required area to accommodate the expansion of the cross section of each specimen was calculated using a typical Poisson's ratio of 0.46 for polyethylene, which suggested that 3" by 3" for each specimen would be more than enough area to prevent any contact. The combination of these required areas and the necessary space for the bolt holes and spacers resulted in the total 12" by 12" area. The orientation of a typical apparatus loaded with specimens is shown in Figure 2.2.

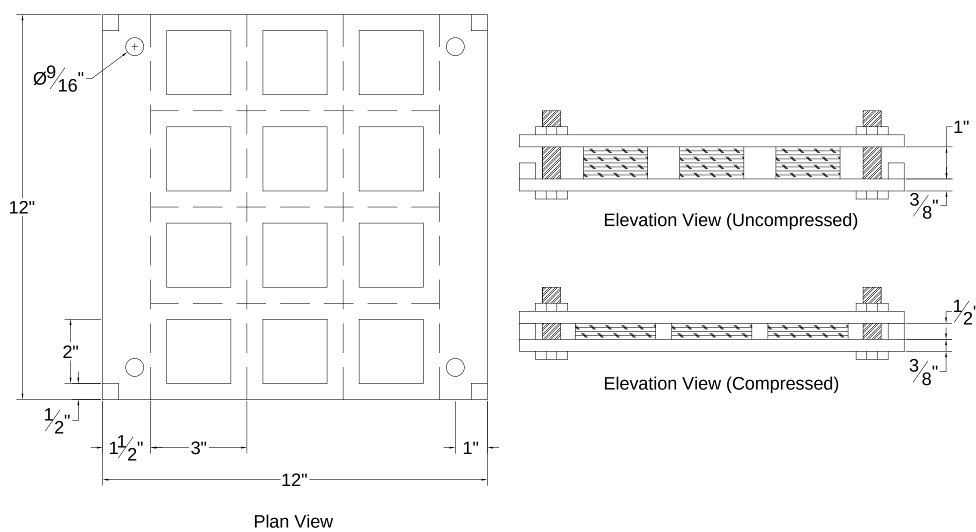


Figure 2.2 Design Sketch of Testing Apparatus

Due to the particular importance of thickness measurements to this study, the procedure for measuring each specimen was performed exactly as described in the standard. To ensure repeatability in addition to precision, the standard requires the use of a dial gauge with a minimum foot area of 1 in^2. The standard also requires the dial gauge to exert a maximum of 0.035 psi on the specimen, as to not cause significant deformation while collecting measurements. The thickness of each specimen was also required to be calculated as a five point average of the thicknesses measured at the center, and four equally spaced locations around the perimeter, so the corners were selected as the measurement points. A simple mounting station was erected to support the dial gauge using an adjustable arm and a magnetic base. The dial gauge was calibrated using precisely cut ½" cubes of key stock that were also used as spacers for the compression apparatuses, after which the station was fixed in its position to ensure repeatability of the measurements. Each specimen's thickness was measured at each corner and the center to calculate the five point average (Figure 2.3), and the key stock was periodically measured to ensure that the station had not shifted during use. Once the average original thickness of each specimen was calculated and recorded, the compression cycling could begin.

Figure 2.3 Mounting Station and Dial Gauge, Corner Thickness (left); Center Thickness (right)

The bottom plate of each apparatus was marked to indicate the exact placement of each specimen in accordance with the design shown in Figure 2.4. Once all 12 specimens for a given trial were in place, the top plate was applied such that the bolts could be passed easily through the holes in the corners of the bottom and top plate and secured by nuts on the exterior surface. The standard requires that the specimens be compressed to half of their original thickness, so the cubes of key stock were placed in each corner of the apparatus as to not interfere with the specimens. Clamps were used to initially compress the plates until they made snug contact with the key stock spacers, ensuring a compressed thickness of ½”. The nuts were then screwed down to secure the plates, allowing the clamps to be removed.

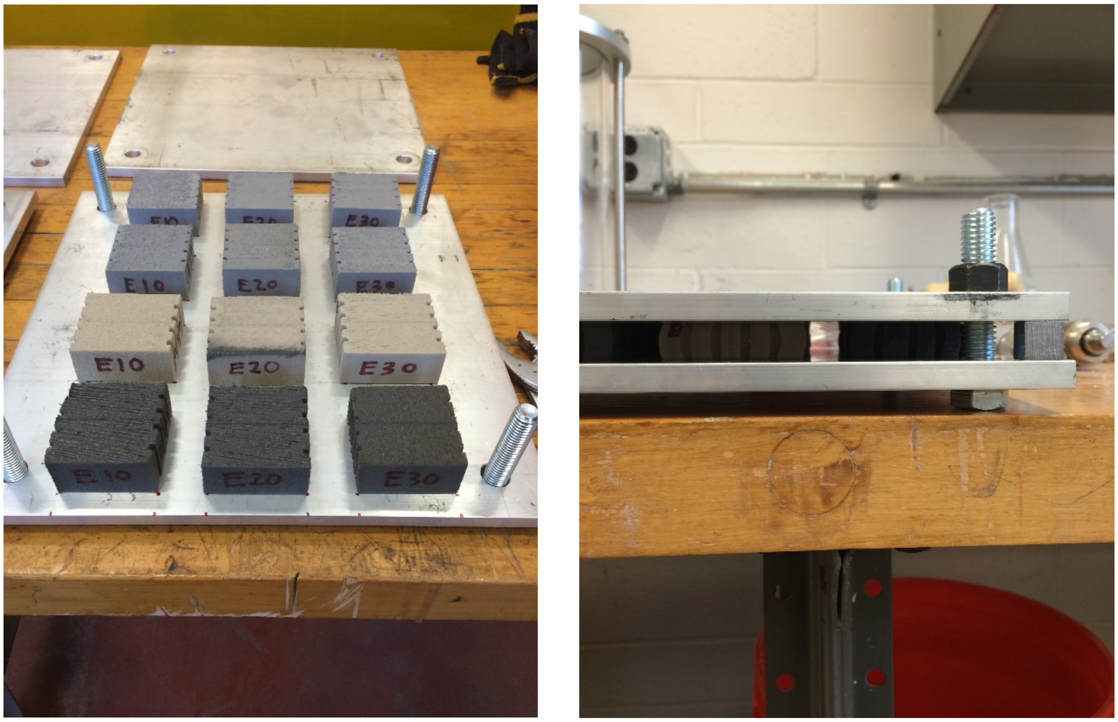


Figure 2.4 Specimens Loaded in Open Apparatus (Left); Specimens Compressed to 0.5 Inches (Right)

This process was repeated for 4 separate sets of specimens, each being held for different compression cycle durations. The first trial used the 22 hour compression cycle required by the ASTM standard, while three other trials were held for compression cycles of 1, 2, and 3 months, all at an ambient temperature of 73° F as prescribed by the standard. These durations were meant to better represent the compression cycles that joint gland material experiences in service, as thermal expansion in bridges occurs over the course of months. Also, in an effort to better represent the elevated temperatures that these materials may experience during the summer months in warmer regions of the country, four additional trials were run for the same four compression cycles, but kept in an oven for the entire cycle which kept the samples at just below 110° F (43° C). This elevated temperature value was decided on by investigating the average daily temperature of Phoenix, Arizona (the city with the warmest recorded summers in the U.S.), between the months of June and August. By analyzing the temperature data presented on WeatherSpark's website, the average daily temperature remains around 105° F during these months, reaching just under 110° F at its 90th percentile (WeatherSpark Beta). Other manuals were investigated such as the AASHTO LRFD Bridge Design Specifications (AASHTO, 2007), the Arizona DOT Bridge Design Guidelines (ADOT, 2001), and the Texas DOT LRFD Bridge Design Manual (TXDOT, 2013), to determine the value that is used for temperature in thermal expansion calculations (all material investigated is included in Appendix B). All three of these manuals reported values between 115° and 130° F as their maximum experienced temperature to be used in design for material elongation. However, as our experiments required a sustained temperature that these materials might experience continuously over the course of several months, the value of 110° F was selected instead of the more intermittently experienced values of 115°-130° F. The complete testing matrix is shown in Table 2.1 below.

Table 2.1 Compression Set Testing Matrix

Temperature (°F)	Duration	Supplier
73°	22 Hours	Watson Bowman Acme
	1 Month	
	2 Months	Chase
	3 Months	
110°	22 Hours	
	1 Month	Polyset
	2 Months	
	3 Months	R J Watson

Four identical copies of the testing apparatus were fabricated in order to perform all of the testing in one 3 month period. The first experiments to be conducted were the 22 hour and 3 month compression cycles, at room and elevated temperature, which ran simultaneously using all four apparatuses. Upon completion of the 22 hour test, the 1 month tests were initiated using the vacated apparatuses, and the 2 month test followed afterward. Performing the tests in this order allowed the entire testing matrix to be conducted in one 3 month period.

Once the compression cycle in any one test had elapsed, the same procedure was followed for every trial, regardless of cycle duration or testing temperature. First, the apparatus was released from compression by unscrewing the nuts and removing the top plate. The specimens would remain on the bottom plate, untouched for the rebound period of 24 hours as prescribed by ASTM D3575. At the end of this time, each specimen was then measured for its new thickness, using the same dial gauge station as before, and calculated by the same five point average. With the original and final thicknesses recorded, the compression set value for each specimen could be calculated. The constant deflection compression set, as prescribed by the standard and expressed as a percentage of the original thickness, is equal to the difference of the original and final thicknesses, divided by the original thickness (Figure 2.5). Using the five point averages recorded from the original and post-compression specimens, the compression set was calculated for each specimen. The values for the three replicates of each supplier were then averaged, to produce a single compression set value for the material of each supplier.

$$C_d = \frac{(t_0 - t_f)}{t_0} * 100$$

$where$:

$C_d = compression\ set\ expressed\ as\ a\ percent\ of\ the\ original\ thickness,$
$t_0 = original\ thickness, mm\ (in.), and$
$t_f = thickness\ of\ the\ specimen\ after\ the\ specified\ recovery\ period, mm\ (in.)$

Figure 2.5 ASTM D3575, Equation for Compression Set

2.2.2 Rebound Tests

The follow-up study on rebound duration, prompted by the analysis of the compression test data, did not require any physical experimentation, only a continuation of the final thickness measurements that had been taken at the conclusion of each compression cycle. To ensure rebound duration was the only parameter being investigated in this study, the same thickness measuring apparatus from the compression tests was used. Also, the tested specimens that were to be remeasured for this study were stored at room temperature and allowed to rebound freely, as directed by the current standard. Because these were the same specimens that were prepared and tested in exact accordance with ASTM D3575, allowing them to continue to rebound freely at room temperature ensured that the only modification being made was to rebound duration.

During the compression tests, the compression cycle duration was modified from 22 hours to be on the order of months. In selecting the rebound duration for this study, it was logical to make a similar modification and analyze a rebound duration on the order of months as well. It was decided that measurements were to be taken once a week over the course of a 3 month period, to match the maximum compression cycle duration. These measurements were taken using the same apparatus, as well as the same 5 point averaging technique. The new final thickness of each specimen could then be averaged over the three replicates of each supplier, and a new single compression set value calculated using the equation from the standard. The compression set for each supplier computed once each week were plotted against time to investigate the effect of rebound duration on compression set.

This study investigated the rebounding behavior of the 1, 2, and 3 month compression cycle specimens exposed to room and elevated temperatures, but it did not collect any additional data for the 22 hour specimens. Due to the order in which the compression tests were conducted, the 22 hour specimens had been freely rebounding for more than 3 months, and the period of useful data that would have applied to the scope of this new study had expired. In addition, the extended rebound durations were meant to match the compression cycles, hence the 3 month collection period of rebound data. In the case of the 22 hour compression cycle specimens, their compression set had already been calculated with a comparable rebound duration during the original compression test, so any analysis conducted on extended rebound periods would have limited application to the scope of this study.

2.3 Results and Discussion

2.3.1 Compression Tests

The final compression set values for the CCFs from each supplier are presented in Table 2.2 below. Once again, each value represents the average of the three specimen replicates. This table includes the results for the standard 22 hour test (labeled as “1 day”), alongside the results of the modified compression cycle duration tests. The results of their elevated temperature counterparts are also included for comparison.

Table 2.2 Final Compression Set Data, Expressed as Percent Loss in Original Thickness (Figure 2.5)

	73°F				110°F			
Supplier	1 Day	1 Month	2 Months	3 Months	1 Day	1 Month	2 Months	3 Months
A	12.9%	22.9%	25.3%	28.1%	39.7%	42.4%	43.5%	44.2%
B	12.1%	22.2%	25.7%	27.7%	39.8%	41.1%	42.9%	45.4%
C	11.9%	28.4%	32.6%	34.6%	47.0%	45.5%	47.2%	48.3%
D	11.1%	23.5%	27.5%	30.4%	46.1%	46.6%	49.8%	49.0%

The specimens that were tested at room temperature with a 22-hour compression cycle represent the original testing method prescribed in the standard, and as such can be compared with the values reported by the suppliers. It is important to note that the make-up of the 4 materials tested is very consistent, and that there is not a large amount of variability between the individual manufacturers. According to the data sheets for these materials, the reported compression set for their products lie in the 9-10% range. As seen in Table 2.2, the compression set measured in this investigation was just slightly greater, in the 11-13% range. The small discrepancy between these two sets of data can likely be attributed to variations in the measuring process, such as a difference in the pressure inherent in the dial gauges, or the quality of the batch of material tested by the suppliers, compared with the batch that was tested in this study. The values reported by the manufacturers are also most likely the average results from many different lots of material, and not a sample from just one lot. Though slightly greater, these compression set values validate the quality of the procedure conducted in this study, as the results are close to those reported by the suppliers. The names of the suppliers are disassociated with the results of their foam product in Table 2.2 in order to inhibit the direct comparison of performance between two suppliers. This project tested multiple products only to increase the confidence of the results, and evaluating the performance of any single supplier's foam was not included in the scope.

Comparing the room temperature 22-hour values with their elevated temperature counterparts reveals an approximately 300% increase in compression set as a result of the increased temperature alone. Considering that the specimens were held at 50% of their original thickness during the compression cycle, the values that were measured to be between 46-47% represent material that hardly rebounded at all, i.e., only around 3-4%. By comparing elevated temperature data with the room temperature data, or with the 50% compression set that was present during testing, it is clear that temperature has an enormous effect on the performance of these closed cell foams during testing. As temperatures are unlikely to remain near the 73° F mark suggested by the current standard when these joint seals are compressed to their maximum in the field, this prescribed temperature may not be appropriate in evaluating the performance of this material in all regions of the country.

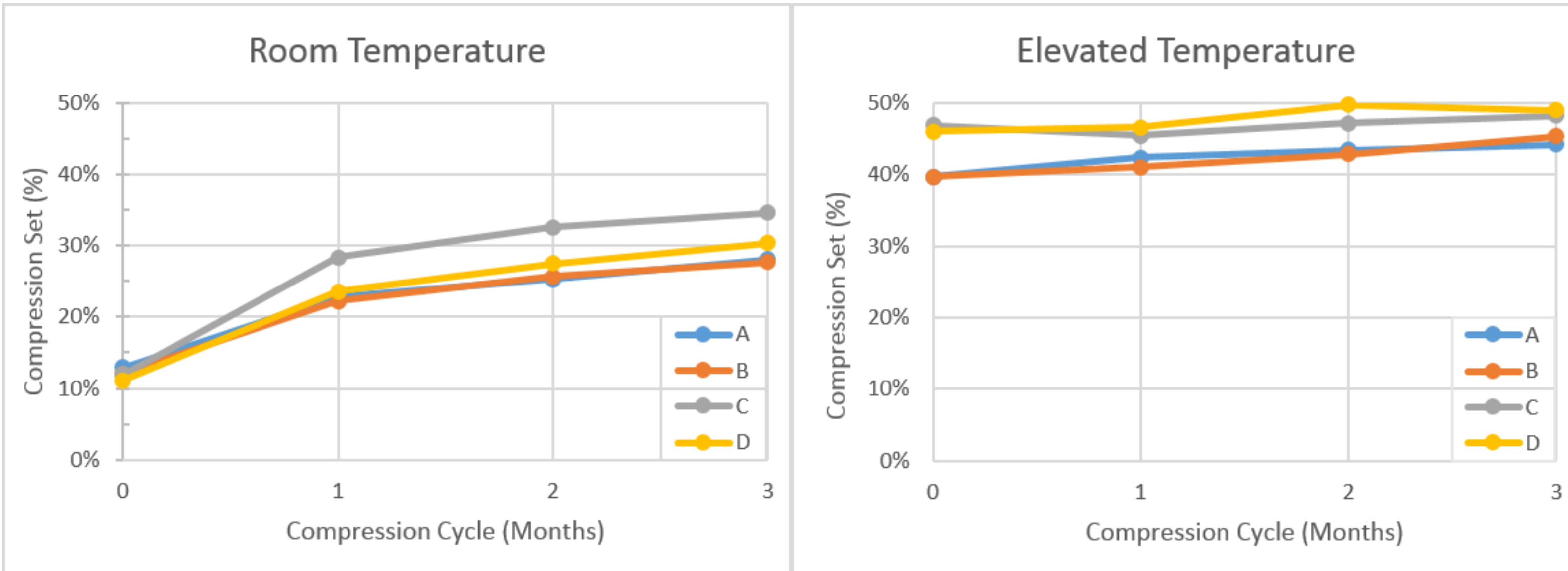


Figure 2.6 Compression Set for Room Temperature Trials (Left); Compression Set for Elevated Temperature Trials (Right)

The graphical representation of the compression set data in Figure 2.6 facilitates the comparison between the compression cycles. Considering the elevated temperature trials first (Figure 2.6, right), it can be seen that while very gradual, there is a general increase in compression set as the cycle duration increases. The correlation between compression set and cycle duration is likely being masked by the extreme effects of the elevated temperature, which were discussed above. In spite of these effects, the values still exhibit a linear increase in compression set with cycle duration. A more indicative portrayal of the effects of compression cycle is found in the room temperature trials. When the compression cycle was increased from the standard 22-hours to the shortest of the new experimental cycles, the 1 month trial, all materials experienced a 100% increase in compression set. Though the gradient between the three longer compression cycles is not quite as large, there is a clear linear correlation between increasing cycle duration and compression set. It is clear from these results that the duration of the compression cycle has a significant effect on the results of this test, with up to a 150% increase in compression set between the current standard and longest cycle. As the longer cycles are a much more accurate representation of in-service conditions of bridge joints, the significant difference between these results and the testing standard suggest that a more appropriate compression cycle duration could be selected for this test to increase its accuracy for these types of materials.

For both temperature and cycle duration, it is apparent that the current ASTM D3575 testing standard may not be an appropriate compression set test for all joint material in all regions of the country. The significant difference between the testing results of the current standard and new trials designed to better simulate in-service conditions show that several improvements to the standard as it applies to CCF bridge joints are possible. Modifications to the compression cycle for these types of materials would increase its accuracy, as would a testing temperature that varied based on service region. In the absence of these modifications, in order to avoid instances of tensile stress in the joint gland caused by this lack of rebound, it may benefit designers to be more conservative when selecting the size of the gland material, as the results of this study show that the compression set data reported by the suppliers may not always be accurate for every in-service situation.

2.3.2 Rebound Tests

The graphs in Figure 2.7 represent the modified compression set values calculated with the final thickness measurements collected during the extended rebound duration test. The y-axis represents the new compression set, and the x-axis represents the rebound duration in days, or the amount of time between the completion of the compression test and the measurement of its new final thickness. These graphs display data for room and elevated temperature specimens, but only for the product of one supplier. This figure is presented as a typical example of the results of this study, and the full collection of results for all suppliers can be found in Appendix C. Regarding the different foam products, there did not appear to be any major difference between any of the suppliers. There were small differences in magnitude of compression set, and in correlation of compression set and rebound duration in rare cases. Just as in the compression set study, the differences between suppliers was not significant in general.

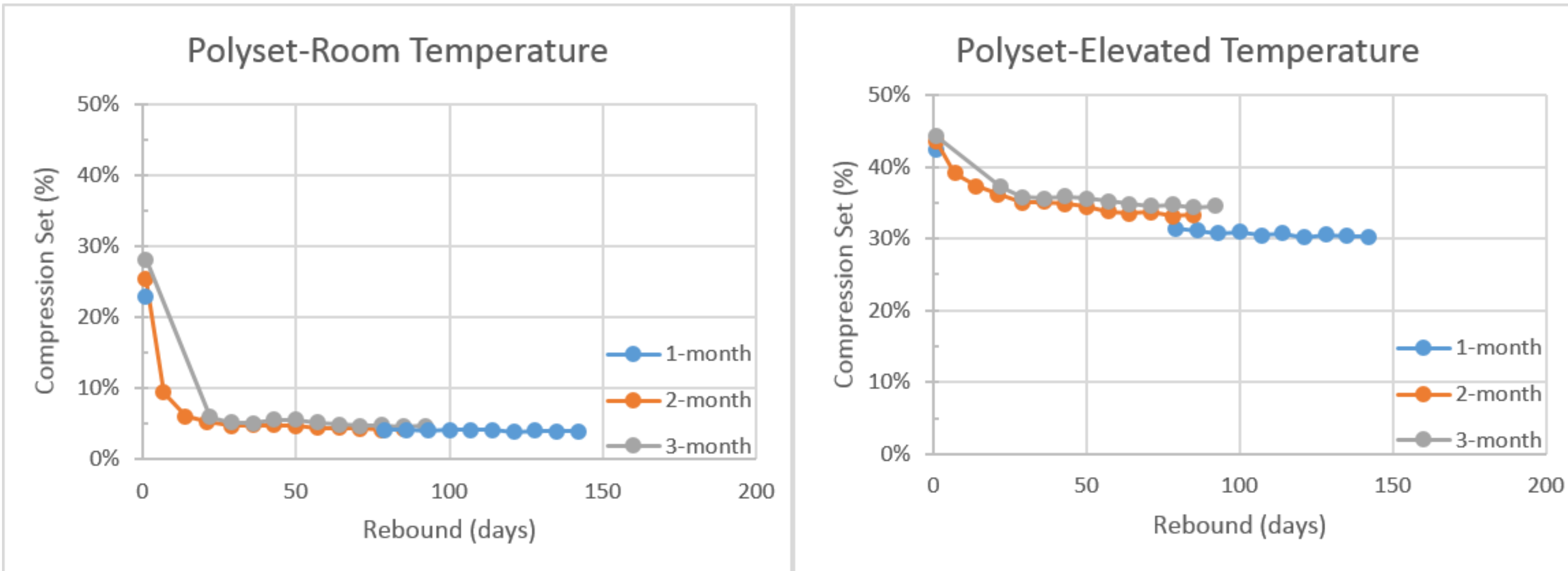


Figure 2.7 Compression Set Data for Extended Rebound Durations

These graphs may also appear to have gaps in the data, with the most apparent of these being in the 1 month series between 0 and 75 days of rebound. These gaps are a result of the way in which this study began, and the order in which the compression tests from the previous study were conducted. Because the decision to perform this study was made after the conclusion and analysis of the compression experiments, some specimens had already been rebounding freely for a much greater amount of time than others. Thickness measurements began on all specimens as soon as the study began, but because the 1 month compression test was concluded before the 2 month test began, there was roughly 2 months of rebounding that had already occurred in those specimens when the decision to conduct the rebound study was made. The 3 month compression test was also completed a few weeks before the 2 month test, because of the testing schedule described in the procedure, so it also has a few weeks' worth of absent rebound data. As will be explained further in the discussion, the data from this study showed that the most significant portion of these trends came after long periods of rebound, so these gaps near the beginning of some of these tests were not considered to be a hindrance to the findings of this study.

The most apparent and important finding of this study demonstrated in Figure 2.7 is that regardless of the supplier, compression cycle, or testing temperature, closed cell foam will continue to rebound after the first 24 hour period. Comparing the y-intercepts of these graphs (which represent the compression set calculated after a 24 hour rebound period) with the compression set calculated at any amount of additional rebound time, shows a significant reduction in the amount of retained compression set. The trends of the individuals series in Figure 2.7, and the rate of decrease in compression set is also a point of interest. Focusing first on the room temperature graph, all specimens experience a significant decrease in compression set, followed immediately by a horizontal asymptote that remains unchanged over the remainder of the rebound period. Regardless of the applicability of these rebound periods to in-service situations, these horizontal asymptotes represent the true compression set of the material. For all compression cycles, it appears that approximately 1 month of rebound will result in compression set values in the 4-5% range, which are then unaffected by continued rebounding. This horizontal asymptote reveals a few details about the nature of CCFs. First, all foams level off at a compression set value that is about half of what is reported by manufacturers (which usually lies in the 9-10% range), undoubtedly due to the brief rebound period prescribed by the current standard. Also, while the series for the 1 month compression cycle is incomplete, it does offer insight into the behavior of this foam at an extreme rebound duration. Yielding an unchanging amount of compression set after almost 5 months of rebound strongly suggests that closed cell foams experience permanent losses in thickness, and will never completely return to their original dimensions. Lastly, while the value of each asymptote is exceedingly similar for each compression cycle, there is a small discrepancy that suggests a relationship between compression cycle and true compression set. The value of the asymptote is slightly less for specimens that experienced shorter compression cycles. Though only a slight correlation, this suggests the intuitive idea that the longer foam is compressed, the more compression set it will retain.

The results for the elevated temperature specimens bear many similarities, with a few key differences. These graphs also exhibit a period of decay followed by a horizontal asymptote, but the magnitude of decay is much less than the room temperature specimens. This is likely due to the effect of elevated temperature observed in the compression tests, where temperature has such a large effect on compression set that the influence of time (rebound duration in this case, and not compression cycle duration), is much less significant. This effect can also be seen in the magnitude of the asymptote, which levels off in all cases between 30-35%. These values of compression set are higher than all values calculated for the room temperature specimens, including the 24 hour rebound values, and especially the asymptote values of 4-5%. This study agrees with the compression study in that even in the case of rebound duration, temperature has the most significant effect on compression set retention. As with the room temperature specimens, the horizontal asymptote is reached after about 1 month of rebound, but the asymptote itself is not quite as stable. After leveling off, most specimens still experience approximately 1% additional reduction in compression set, which may be due to the higher levels of total compression set. These high levels may make it more difficult for the material to maintain its thickness, even after extended rebound durations. Lastly, the same correlation between compression cycle and compression set retention exists in the elevated samples (longer cycles retain more compression set), but the variance between the individual series is much greater. This can be noted by visual inspection, where the asymptotes on the elevated graph have distinctly different values, where the series on the room temperature graph are almost completely overlapping. This may also be due to the higher total levels of compression set, and yields even stronger evidence that compression cycle does have a significant effect on compression set retention.

The objective of this study was to investigate the appropriateness of the 24 hour rebound period prescribed by the current ASTM standard for the testing of compression set in CCFs. Just as with compression cycle, a testing procedure occurring on the order of hours seemed unrepresentative of the conditions these foams experience while in service, which take place on the order of months. Though the temporary heating and cooling period a bridge joint may experience on any given day will be on the order of hours, the global temperature cycle through which joints experience the largest thermally induced stresses takes place undoubtedly over multiple months. The final thicknesses of the foam specimens that underwent the compression test were continually measured, in order to calculate the experimental compression set at various rebound periods over the course of 3 months. The results of these calculations show that for all varieties of foam, compression cycle, and testing temperature, the specimens will continue to rebound a significant amount outside the prescribed 24 hour window. Comparing these results with the current standard yields different findings based on the temperature of the compression test. For the room temperature specimens, after about 1 month of additional rebound, the specimens reach a true compression set of about 5%, which is only half of the typically reported values by CCF manufacturers. This means that compared to the more realistic compression cycles and rebound periods experienced during these investigations, the current testing standard may be over-reporting levels of compression set. For room temperature conditions, if the standard was modified (as it applies to CCF in bridge joints) to contain more realistic compression cycles and rebound periods, according to these results, manufacturers would be reporting half as much as compression set as the current standard predicts. For the elevated temperature tests, the reduction in compression set retention was not as drastic. Similar to the room temperature specimens, a true compression was reached after about 1 month of rebound, but this value remained between 30-35% for all compression cycles. This data suggests two findings, the first of which was already proposed by the compression study. Regardless of compression cycle, the elevated compression tests yielded much higher values of compression set than the room temperature counterparts, and the effect of compression cycle duration was almost entirely masked by the effect of temperature. Similarly, the rebound tests showed much higher levels of compression set retention in the elevated temperature samples, and a slower decrease in compression set over time. These results from the rebound tests confirm the suggestion from the compression tests that testing temperature has the greatest effect on compression set. The second finding from the rebound tests on elevated specimens, was the value at which the compression set ceased decreasing. At a minimum of 30% compression set, even after almost 5 months of rebound, these values are still 3 times greater than the average reported value using the current standard. Though increased rebound durations do reduce compression set retention in elevated specimens, the current standard under-reports compression set values by a factor of 3. By under-reporting the values of elevated specimens and over-reporting the values of room temperature specimens, the 24 hour rebound period of the current standard was shown to be inappropriate for both testing temperatures.

Chapter 3

TENSION TESTING

3.1 Introduction

The results of the compression and rebound tests showed that compression set exists in closed cell foams, though the literature review reveals that no studies have been conducted on compression set as it applies to CCFs. The data from these tests also showed that the current ASTM standard for determining compression set in these foams is insufficient, yielding values that are either significantly higher or lower than what foams are likely to experience in service in SMEJs. These findings, combined with the lack of prevailing literature on this topic, affirms the notion that compression set is not generally well understood. The ultimate motivation for these studies is to determine if compression set has any significant effects on the performance of CCFs, and more specifically, if it is the cause of any known failures that are presently unexplained.

Bridge owners from many different state agencies have reported failures of CCF joints due to tearing in tension, and as a result some agencies have limited their use of foams to exclude situations where tension is likely to occur. This limitation contradicts the expected performance as reported by the manufacturers of CCFs, whose data sheets list allowable movement in tension between 20-30%. Clearly there is a disconnect between the suppliers and bridge owners when it comes to the expected performance of these foams, and it seems that something is degrading their performance while they are in service, which is not occurring during the production and testing by the manufacturer. Since compression set has already shown to be a poorly understood and inaccurately reported phenomenon, it is possible that it is the cause of the underperformance of CCFs in tension.

In this work a series of experiments were designed to determine if compression set is indeed causing or contributing to the failure of foams in tension. This was accomplished by simulating as accurately as possible the conditions experienced in service by the foam. To do this CCF samples were first bonded between steel plates using the manufacturer's adhesive, then compressed and held for a specified duration and at a specified temperature. At the end of the compression cycle the specimens were released and immediately placed in a universal testing machine and tested in tension to failure. The key questions to be answered by these tests are: (1) can the foam carry tension, and if so, how much, and (2) what is the mode of failure? If the tensile capacity of both the foam and the bond are high enough to prevent tearing of the specimen in tension after experiencing a compression cycle, it is likely that other factors are inhibiting the foams performance. If the specimens do tear after experiencing a compression cycle, this would be strong evidence to suggest that compression set may be a contributing factor to the failure of CCFs.

3.2 Test Set-Up and Procedure

3.2.1 Compression/Tension Loading Plates

In order to accommodate the specific needs of this new series of tests, a new testing fixture needed to be fabricated. It needed to resemble the apparatus used in the compression test because these specimens needed to experience the same compression cycle, but since the apparatus will also undergo a tensile test, it needed to be compatible with the tension testing machine. Due to the size limitations of the testing machine, and to ensure the quality of each tensile test, the decision was made to test one specimen at a time. Therefore, the apparatus had to accommodate only one specimen, and not twelve as before.

Steel plates were used instead of aluminum, because of the popularity of steel as an armor material for joint headers. This is the material that CCFs would most likely be adhered to in the field, aside from cementitious and polymer-based concretes. The apparatus was designed to include two 6”x6”x1/4” steel plates, and four bolts that will be used to hold the plates in place during the compression cycle. The dimensions of these plates were designed using the same process as before, using a typical Poisson’s ratio of polyethylene to ensure that the expanded specimen would not come into contact with the bolts. Six pairs of plates were cut out of a ¼” sheet of steel, and the necessary bolt holes were drilled in each. The same bolts, nuts, and spacers were used from the compression study. A photograph of the new fixture in the closed position is shown in Figure 3.1.

Figure 3.1 Single Compression/Tension Specimen Fixture in Closed Position

The same varieties of CCF were used as in the compression tests. For this series of tests, the specimens were cut into 2”x2”x2” cubes, instead of the ASTM prescribed 2”x2”x1” samples. Assuming the material is isotropic, the orientation of the foam did not matter for the compression tests. But for an adhered tension test, because the grooved sides must be used with the adhesive, the orientation does matter. The only way to create a specimen with grooves on both sides, and with a 2”x2” cross section is to use a cube. These samples were cut using the horizontal band saw and labeled appropriately as before.

3.2.2 Adhesion and Compression Cycle

In order to determine the effect of compression set on CCFs in tension, the most important objective of the testing process was to simulate a complete compression-tension cycle for an in-service foam as accurately as possible. To ensure this, and to have confidence in the results of the testing, a procedure must be followed that creates a strong and reliable bond between the foam and the header material. If such a procedure is not followed, any poor performance of the foam could be blamed on the integrity of the bond. Though most of the adhesives used for CCFs are similar, each supplier recommends the use of their own product and installation procedures. Following these recommendations for this procedure not only ensures bond quality, but will also best represent ideal construction conditions, since these are the exact combination of products used in joint installation. Adhesive product was ordered from each of the four suppliers whose foam was being tested, and great care was taken to follow the installation procedures provided with the adhesive. Assuming that bridge joints in the field are installed properly and in accordance with the supplier’s instructions, following these same procedures should produce test specimens that are as similar as possible to their in-service counterparts.

The adhesive provided by all CCF suppliers is a two component moisture insensitive modified epoxy adhesive. The epoxy is formed by either combing the entirety of both components (for large installation jobs) or combining 3 parts component A with 1 part component B (for small installation or maintenance jobs). Having only 6 fixtures available at one time, the latter option was selected, and about 2 cups of epoxy was prepared for each testing cycle. According to the procedure, the mixture is to be stirred to combine both parts evenly and eliminate marbling, which should take about 3 minutes. The procedure also includes a section on header preparation, specifically referring to steel armored headers. To ensure a strong bond, the steel is to be ground or blasted to remove all oxidation and reveal "white steel". This was achieved by using a disc grinder, and all plates were ground to be in adherence with the procedure. With the fixtures, the foam cubes, and the epoxy prepared, the bonding process could begin.

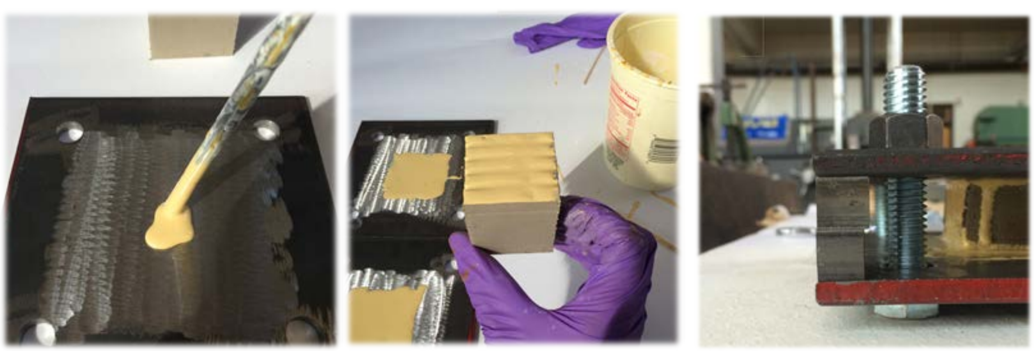


Figure 3.2 Applying Epoxy to Steel (left); Epoxy Applied to Grooved Foam (center); Compressed Plates with Loaded Foam Specimen (right)

The first step is to apply a layer of epoxy to both sides of the header, about 1 mm thick. The procedure is not specific as to what type of implement is to be used to apply the epoxy, so for the small scale purposes of these tests a popsicle stick was used to apply and smooth out the epoxy. The second step is to apply the epoxy to both of the grooved sides of the foam.

Figure 3.3 Section View of Foam Grooves; Epoxy Coated (top) and Vacant (bottom)

These grooves (Figure 3.3) are cut into two opposing sides of the foam during manufacturing, in an effort to increase the surface area of the bond. All CCFs are produced with these grooves, and the size and amount of grooves on each brand of foam tested were essentially identical. The epoxy is to be worked into the grooves as shown in the center image of Figure 3.2, which was accomplished again using a popsicle stick. Lastly, the foam is to be inserted into the open joint in between the headers where the epoxy was applied. For this test procedure, this equates to placing the coated side of the foam cube onto one coated plate, and placing the other plate on top of the foam. To simulate the compression of the joint, just as in the compression tests, bolts are passed through the holes at each corner and secured with nuts. Spacers are inserted to ensure that the testing thickness is 1”, half of the original. The final step in preparing these adhered specimens in accordance with the supplier’s procedure is to clean the foam of any excess epoxy. When trying to squeeze a coated piece of foam into a joint in the summer months when the gap is relatively small, there will naturally be excess epoxy that runs onto the side of the foam. Likewise with these tests, a significant amount of excess epoxy would run down the sides of the specimen when the apparatus was put into compression. The procedure does not explain why this is important, but some of the findings of this study demonstrate why excess epoxy can be detrimental to the integrity of the foam in tension. After the apparatus was put into compression, a popsicle stick was used to remove any excess epoxy from the foam and plates, so that none of it could dry on the non-grooved faces of the foam sample. Once this step was completed, the specimens were prepared for the compression cycle portion of testing.

Table 3.1 Tensile Performance Test Matrix

<table>
<tr><th>Temperature (°F)</th><th>Duration</th><th>Supplier</th></tr>
<tr><td rowspan="2">73°</td><td>22 Hours</td><td rowspan="4">Watson Bowman Acme
Chase
Polyset
R J Watson</td></tr>
<tr><td>1 Month</td></tr>
<tr><td rowspan="2">110°</td><td>22 Hours</td></tr>
<tr><td>1 Month</td></tr>
</table>

The test matrix for this study (Table 3.1) was formed using the same logic as with the compression testing. As a large portion of our country's bridges experience significantly warmer temperatures in the summer months, half of the tests were conducted at an elevated temperature of 110° F. Just as before, the specimens were stored in an oven to maintain this environment. Endeavoring to make the tests as realistic as possible, a portion of the tests were tested for a 1 month long compression cycle, in addition to 22 hour trials. These longer durations are a much better representation of what a bridge joint will experience in the field. Due to time and apparatus limitations, a 1 month compression cycle was the longest cycle that could be tested. Because the specimens were tested one at a time, instead of twelve at a time, multiple compression cycles could not be run concurrently. For 4 different suppliers, 4 1 month tests took 4 months, and not 1 month as before. This abridgement in compression cycle was not believed to limit the findings of the study, as the results from the previous compression tests showed that the least amount of change in data occurred between the longer month cycles. Especially for the elevated tests, once a specimen has been compressed for a month, another month or two does not make a large difference. For consistency, 3 replicates of each foam were tested just as before, in order to report a more reliable average of results. Once the compression cycle was finished, the specimens would be immediately subjected to a tensile cycle.

3.2.3 Tension Testing

The machine used for the tension test was a Lloyd T50K Testing Machine. While this machine has a maximum tensile capacity of 50,000 N, which is far beyond the small amount of force needed to deform the foam specimens, it was selected because it is displacement controlled. While other testing machines cycle specimens according to stress levels, the Lloyd machine uses displacement as its independent variable. The displacement of the test is controlled by a single input dial, in which the operator selects the displacement rate, shown in the right image of Figure 3.4. Unfortunately, simulating a realistic tension cycle of a bridge joint is impractical: bridge decks experience thermal expansion at rates around 1 inch per month. Even if the electromechanical devices in a testing machine could maintain a reliable level of performance at such a slow pace, which most cannot, the amount of time necessary to test 3 replicates for 4 suppliers at multiple temperatures and compression cycles would be on the order of years. Instead, the tension cycles were run at the slowest pace that the machine could reliably operate. For this particular machine, this rate was 2 mm/min, which equates to 4.72 in/hour. While not technically realistic, this rate was at least conservative. Since there is no reason to believe that a slower pace would ever be more detrimental to the strength of the foam, this much faster rate of displacement will represent an extreme worst case scenario for the material. A foam product in the field will likely never experience displacement at such an accelerated rate, so if the foam were to perform well under these conditions, it can be implied that they would perform at least equally well while in service.

Figure 3.4 The Lloyd T50K Testing Machine (left); Crosshead Speed Dial (right)

The Lloyd tester has two cylindrical metal columns with pins on one end called crossheads that are used to anchor the specimen in the machine. The simple pin and hole design was not compatible with the compression apparatus directly, so an intermediate fixture had to be fabricated that could fasten to the crosshead and also to the plates of the compression apparatus. These fixtures consisted of a steel plate with holes matching the holes in the compression plates that was welded to a piece of steel pipe that would interlock with the crosshead. The bolts that had been used to keep the specimen in compression were used to secure each plate individually to one of the crossheads, and allowed the machine to put the specimen in tension. Once the compression cycle was complete, the specimens could begin their tension cycle, one at a time.

The first step in preparing the specimens for tension cycling was to remove one of the four bolts. With three still in place, the foam would not be permitted any significant rebound. The specimen was then loaded into the machine in between the two fixtures, and the crossheads were lowered to hold the specimen in place (Figure

3.5, left). This was to ensure that the specimen would not rebound while the other bolts were removed. One by one the bolts were removed, and the specimen was slid into place, such that the holes from the apparatus lined up with the holes of the fixtures. Bolts were then used to secure the plates to the loading fixture. Just after the beginning of the test, enough space would exist for the spacers to also be removed. Before the cycling could begin, the zero function was used to tare the load and extension. It was very important that the readings given by the machine reflected that the starting position, when the thickness of the foam was 1 inch, represented an extension of zero. With the extension rate set to 2 mm/min, the tension cycling could begin.

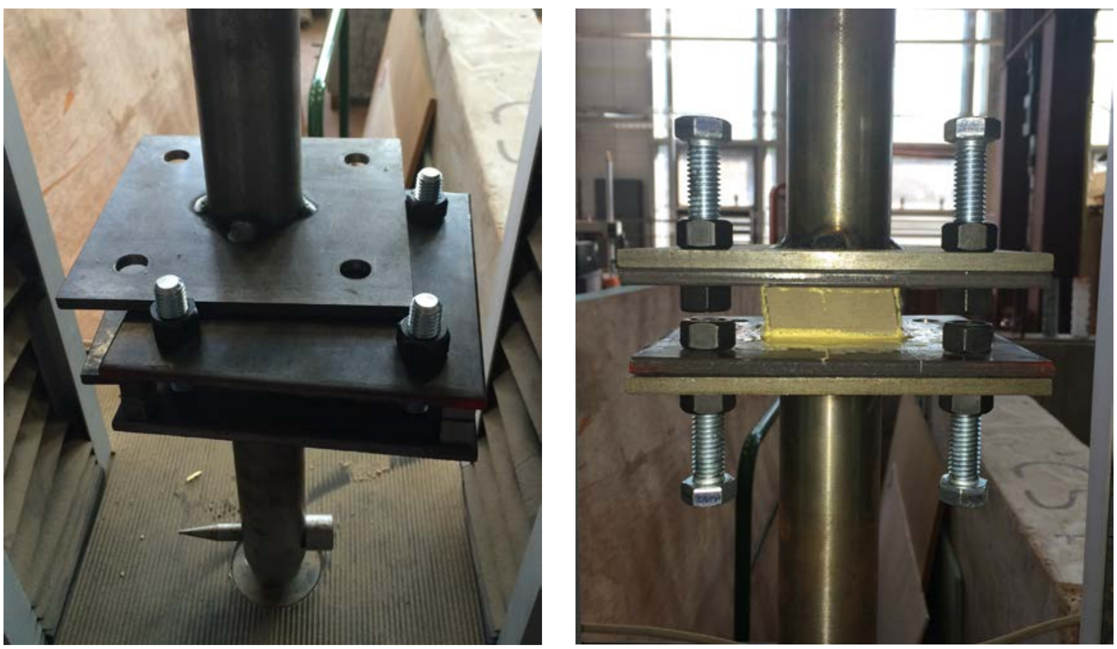


Figure 3.5 Preventing Rebound While Loading Specimen (left); Loaded Specimen (right)

The machine produces output readings of load and extension. In order to monitor the performance of the foam, and perform post-test analysis, readings of load and extension were recorded by hand once every minute. The test was originally designed to determine if the foam could reach its reported levels of acceptable extension in tension, which is usually between 20-30%. As such, it was decided that the test would continue extending the foam at the same extension rate until this point was reached, at which point the test would continue, unless the sample had failed. All tests on samples that exceeded this value continued until the foam specimen failed, no matter how much total extension occurred (Figure 3.6). Failure in this case means complete tearing of the foam, though any minor or intermediate tearing was noted. Allowing all specimens to fail before concluding the cycling allowed the test to collect a vast amount of useful data on the manner in which these foams fail.

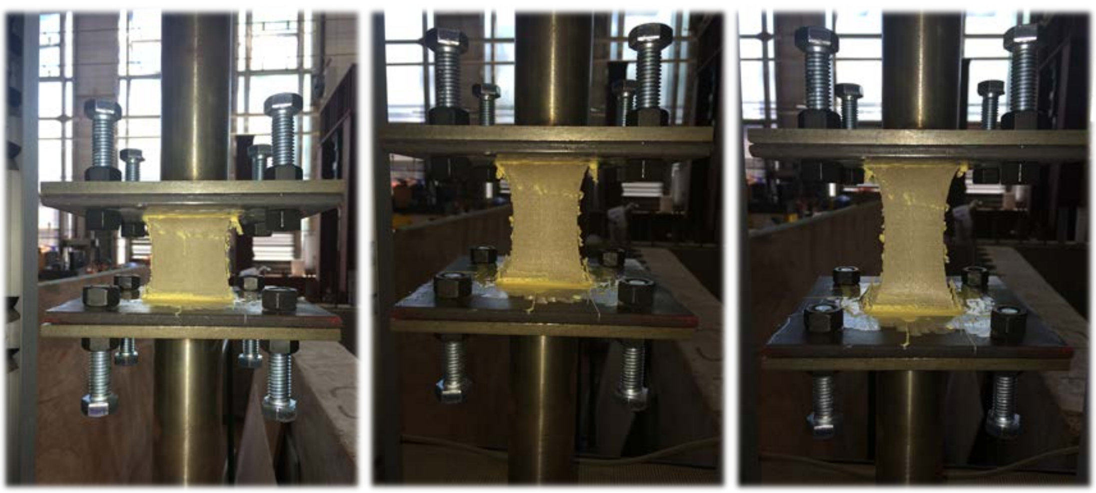


Figure 3.6 Foam Specimen Extension During Tension Testing

3.3 Results and Discussion

Table 3.2 Ultimate Elongation Expressed as Percent of Original 2” Thickness

	73°F		110°F	
Supplier	1 Day	1 Month	1 Day	1 Month
A	82.4%	93.9%	72.6%	84.1%
B	79.0%	92.8%	83.8%	94.2%
C	110.2%	82.3%	83.4%	78.3%
D	69.4%	84.1%	92.0%	78.0%
Average	85.2%	88.3%	82.9%	83.6%

$$E_U = \frac{(t_f - t_0)}{t_0} * 100\%$$

$where$:

$E_U = ultimate\ elongation\ expressed\ as\ a\ percent\ of\ the\ original\ thickness,$
$t_0 = original\ thickness, (2\ in.), and$
$t_f = thickness\ of\ the\ specimen\ at\ failure\ (in.)$

Figure 3.7 Equation for Calculating Ultimate Elongation

The ultimate objectives of this study were to investigate the performance of CCFs in tension, evaluate the accuracy of tensile capacities reported by foam suppliers, and determine if the onset of compression set in the field could be causing the premature failure of foams in tension as reported by bridge owners. As foam suppliers usually report allowable tension as a percent elongation (Figure 3.7), this was the most important type of data collected from the tensile tests in this study, and is presented for each supplier, compression cycle, and testing temperature in Table 3.2.

Comparing the values from this study with the values typically reported by suppliers (20-30%) immediately shows that foams that were subjected to a compression cycle, therefore experiencing compression set, not only met but exceeded reported values. Though the values differ from supplier to supplier, none of the maximum elongations falls below 69%, and the averages for all compression cycles and temperatures lie between 80 and 90%. This demonstrates clearly that the foam samples in this study performed favorably in tension, even after experiencing compression set. The specimens that were subjected to a 1 month compression cycle performed slightly better in tension than their 1 day counterparts, particularly with the room temperature tests, with an average increase in maximum elongation of 3%. As the results of the compression tests showed an increase in compression set with compression cycle duration, a positive correlation between compression cycle duration and tensile performance further supports the lack of correlation between compression set and poor tensile performance. That is, in situations where compression set was likely to have increased, tensile capacity increased on average. An increase in testing temperature did reduce the maximum elongation for both compression cycles on average, but only slightly. This agrees with trends demonstrated in all other tests that show elevated temperature inhibiting the performance of CCFs. However, this decrease in maximum elongation is so slight that it is unlikely that an increase in compression set due to increased temperature causes any significant reduction in tensile capacity. All of the elongation data in this study points to the unlikelihood of compression set being a significant cause of poor tensile performance of CCFs.

Though the extension data from these tensile tests was unable to identify compression set as a leading cause of tensile failure among CCFs, other data collected during this study is useful in understanding other aspects of foam performance and failure. One group of data that was found particularly useful, was the observance of three distinct foam failure modes, photographs of which are presented in Figure 3.8. The first of these can be described as a bond failure. Under high tensile load, this failure occurs when the tensile strength of the adhesive bond is weaker than that of the foam, causing the foam to separate cleanly from one of the steel plates. In this case, none of the foam is torn in any way. This variety of failure occurred frequently, and exclusively, in room temperature specimens with a compression cycle of 1 day. At this point in testing it is reasonable to believe that the epoxy, although hardened, has not yet reached its maximum capacity, causing it to fail before the foam. This failure mode does not occur at all in tests at elevated temperatures, or with longer compression cycles, which supports the idea that the epoxy is weakest in its first day of service. While this is intuitive, according the suppliers of this foam, the epoxy should be prepared for use after only 30 minutes. In the field, foams will not experience levels of compression and tension nearly as rapidly as with these tests, but it still interesting to note that the strength of the epoxy begins at a weaker state, and takes a significant amount of time to develop a tensile strength that is stronger than the foam it’s adhered to.

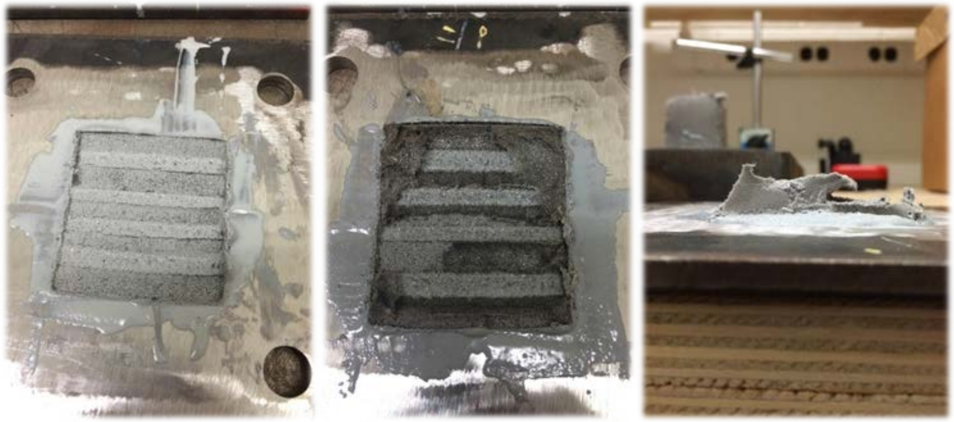


Figure 3.8 Bond Failure (left); Foam Groove Failure (center); Foam Body Failure (right)

The second failure mode can be described as a foam groove failure. In this case, the foam itself tears and is the cause of failure, but this only occurs through the grooves at the edge of the foam sample. As the specimen is put into tension, the grooves that are designed to increase the amount of surface area available for bonding to occur inevitably open up. The thin slices of foam in between the grooves (shown tearing in the top of Figure 3.9) act as ideal failure planes, as they are only a small portion of the thickness of the main body of the foam.

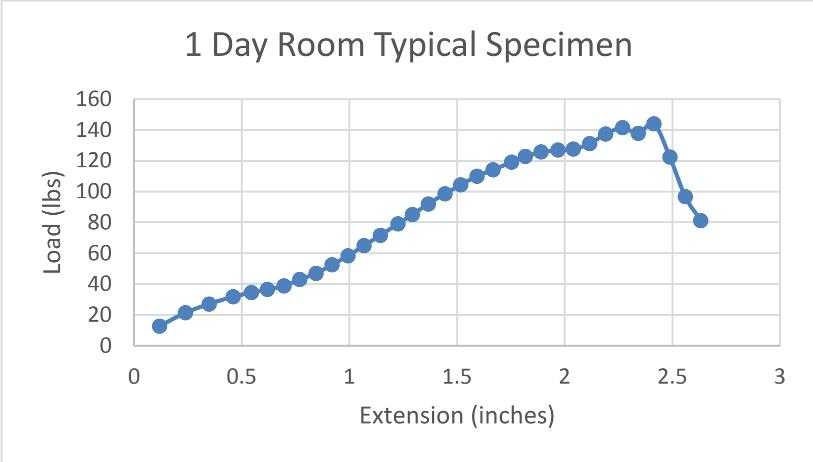
Figure 3.9 Specimen Experiencing Groove Failure

The epoxy in this case was strong enough to maintain the connection between the steel and the foam throughout the entire test. Though the extensions at which specimens failed in this test are extreme, these results introduce the question of the effectiveness of these grooves, and if the additional bonding area gained is worth the theoretical failure plane that is created. These types of failures occur in the vast majority of tests, including 1 day elevated tests, and most of the 1 month tests. This first shows that the epoxy has gained strength over time, for in the equivalent 1 day test, the bond failed first. Secondly, it shows that elevated temperature strengthens the epoxy as well, which performed better than the 1 day tests at room temperature. This is interesting as it appears to improve the quality of the epoxy, while in the compression tests, elevated temperature seemed to be detrimental as it increased the amount of compression set present in the foam. Since analyzing the performance of the joint must include both the bond and the foam, these opposing trends are significant when investigating the performance of a joint at elevated temperatures. The foam may experience higher levels of compression set, but the bond usually increases in strength.

The third and final form of bond failure is a foam body failure. Unlike a groove failure, the tear is generated in the interior body of the foam, and not in the grooves. This failure is very rare, and only occurred in a handful of the specimens. It occurs in the middle stages of tensile testing, when the foam has been stretched past its original length of 2”, but before any extreme extension has been reached. In this situation, there is not enough tension present to open up the grooves on the outside of the foam, so there is no obvious failure plane at the edges yet. At this point, if there are any other discontinuities in the body of the foam that are susceptible to moderate amounts of tension, that is where tearing will originate. The necessary presence of other significant discontinuities in the foam is the reason this failure mode is a rare occurrence. The only discontinuity significant enough to cause this type of failure was due to excess epoxy that dried on one of the side faces of the foam sample. When excess epoxy dries and hardens on a side face, it inhibits the movement of that section of foam. Unable to extend naturally, a stress concentration develops that would not exist if free movement were allowed. These stresses inevitably cause a small tear in the foam, which becomes the new failure plane, and propagates before the grooves can be opened. As seen in Figure 3.10, the tearing begins just at the point where the excess epoxy (labeled in red) ends. This type of failure poses a serious threat to CCFs, and demonstrates why all excess epoxy must be removed from the side faces of the foam, as mentioned earlier in describing the adhering process. In a more general sense, this failure is an instructive example while following all procedures carefully, is essential in the optimal performance of any joint product.

Figure 3.10 Foam Body Failure; Tear Propagation due to Dried Excess Epoxy

The collection of load and extension data once every minute during these tests allows for the development of force-deflection curves for each specimen. The trends in these curves and the similarities between specimens that experienced different compression cycles and temperatures offer additional insight to the performance of CCFs in tension. From the example curves shown in Figure 3.11, it is clear that there are three distinct regions to every curve.



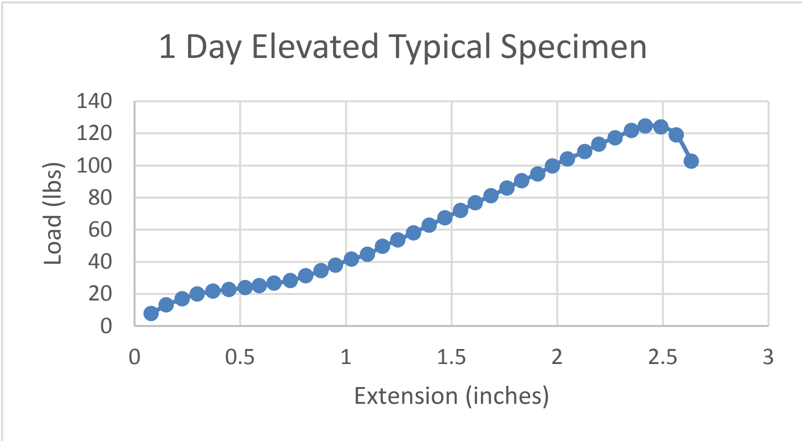


Figure 3.11 Typical Force-Deflection Plots for 1 Day Room and Elevated Specimens

The first of these regions experiences an initial concave down portion, followed by an inflection point and a brief concave up portion (0-0.75”). At the very beginning of the test, the concave down portion of the curve represents the initializing load cell. Since the machine is displacement controlled, the machine must continually increase the amount of applied load until the rate of displacement is reached. After this occurs, the curve immediately drops off at an inflection point, almost to a horizontal tangent. At this point in the test, the specimen is still being held below its original thickness, and therefore tends to rebound naturally. This explains the drop in load required to extend the foam, as it would be naturally extending anyway. As the test approaches the original thickness of the foam, the curve enters a concave up portion, where it begins to require more load per unit time to extend the material. This is also logical, as past its original thickness, the foam would now be naturally resisting movement. The interesting observation from this region is the location of the inflection point. For foam that has not experienced a compression cycle, the inflection point should exist exactly at the 1” mark, which denotes its original thickness. This would imply that only after passing its original thickness would it begin resisting extension. However, the inflection point for every specimen tested occurs before the 1” mark. This is because of compression set. The point to which the foam would naturally rebound is no longer its original thickness, but its thickness minus the existing compression set. For the room temperature samples, the inflection point occurs roughly around 0.75”, which agrees with the average compression set of 25% calculated from the compression tests. For the elevated samples, the inflection point occurs just past 0.50”, which again agrees with the average compression set of around 40-45% from the compression tests (Figure 3.12). This phenomenon not only identifies another method for locating and quantifying compression set, but also proves that the specimens experiencing tensile cycles in this test were indeed under the influence of compression set. This justifies the conclusions drawn about the relationship between compression set and tensile capacity from the data of these tests, by proving that compression set was indeed present.

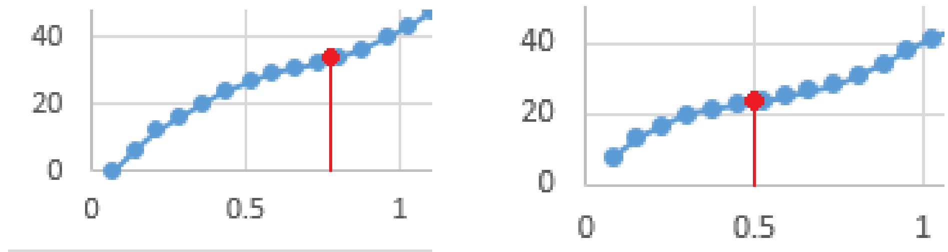


Figure 3.12 Force-Deflection Inflection Points, 0.8” for Room (left); 0.5” for Elevated (right)

The second and third regions of the force-deflection curves include linear-elastic (0.75-2.0”) and failure behaviors (2.0-2.6”), respectively. The interior portion of the curve is intuitive, and contains a perfectly linear relationship between load and extension. This linear-elastic behavior is to be expected, as the name of the material itself, “elastomer”, is derived from these elastic properties. The failure portion of the curve is also intuitive, but has two distinct forms. As seen through the comparison in Figure 3.13, the curves can experience a smooth, or jagged failure. The smooth curves represent a groove failure, when the foam slices between the opened grooves tear suddenly and all at once. The thin slices create a brief loss in the required load for extension, hence the short concave down portion, and then immediately drop off after tearing. The jagged failure curves represent a bond failure. When the foam peels away from the steel without tearing any foam, this happens through one groove at a time. One slice of foam will peel off and reduce the applied load, after which the machine will load back up until enough tension exists to peel off another slice. This will keep occurring until enough slices have separated for complete failure, which gives the curves their jagged shape. Recognition of these trends is useful in identifying the failure of the foam, which otherwise can only be discovered through images of the tested samples.

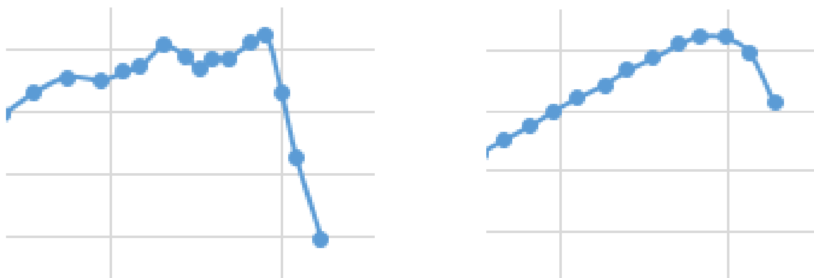


Figure 3.13 Force-Deflection Failure Regions, Room (left); Elevated (right)

Chapter 4

CONCLUSION

Due to a lack of formal guidelines on the maintenance of SMEJs, the research project NCHRP 12-100, “Guidelines for Maintaining Small Movement Bridge Expansion Joints” was developed. Its goal was to investigate the current state of practice of SMEJ maintenance for individual state transportation agencies, and collect resources that could eventually be synthesized into a cohesive national guideline for SMEJ maintenance. Understanding the performance and common issues of these SMEJ products was at the heart of this project, and several smaller studies were conducted in support of this project that investigated specific SMEJ products and performance tendencies that may limit their usefulness. This thesis reports on one such study aimed at better understanding the poor performance of CCFs in tension which has discredited its effectiveness in some regions of the country, and the potentially deleterious effects that contribute to this poor performance, namely compression set.

Through surveys conducted on bridge stakeholders for the NCHRP project, a trend of decreasing popularity in CCFs was discovered. This particular SMEJ was falling out of favor with bridge owners due to increasingly frequent reports of poor performance in tension. The manufacturers of these materials report an acceptable movement range in tension of 20-30%, but many bridge owners have lost confidence in the tensile capacity of CCFs all together, and have limited their use to strictly compressive applications. This clear disconnect between projected and actual performance suggests that something is affecting these materials in the field that does not exist during production and testing by the manufacturers. Due to its frequent appearance in elastomeric materials such as CCFs, compression set was suspected to be the cause of these tensile failures. This permanent loss in rebound due to load cycling likely has a significant effect on the foams ability to perform in tension, as the stresses caused by the loss in elastic properties may cause tearing. Furthermore, there is suspicion that the presence of compression set in CCFs is underestimated, due to shortcomings in the current test standard. Every manufacturer reports a projected amount of compression set that will likely occur in their product, but these values are all derived from the same test included in ASTM D3575. This test prescribes these foams be subjected to a 22 hour compression cycle, followed by a 24 hour rebound period, at 73°F. Since the compression cycles and rebound periods in an actual bridge occur over the course of months, and are subjected to temperatures much higher than 73°F for most of the country, the conditions of this standard test seem inaccurate, and could be producing values of compression set that are far too low.

This study conducted a variety of experiments in order to investigate the performance of CCFs in tension, and determine if compression set is the cause of frequently reported tensile failures. The first of these included performing a compression set test in direct accordance with the ASTM standard, alongside alternate tests with modified compression cycle durations and testing temperatures that better represent in-service conditions. Comparing the results of these tests will evaluate the appropriateness of the current testing standard. A second experiment was conducted to assess the validity of the 24 hour rebound period, also prescribed by the current standard. Just as the compression cycle duration from the current standard was suspected to be unrealistic, the rebound period for CCFs would also be much longer in the field. The thickness of the same specimens from the compression set test were measured over an extended period of two months, in order to calculate the compression set after longer rebound periods. The results were then compared with the 24 hour rebound data, in order to determine the validity of the current 24 hour rebound period. A third and final experiment was conducted to evaluate the performance of CCFs in tension, and gain insight as to why foams in existing bridge joints are failing before the allowable movement range reported by manufacturers. This experiment subjected bonded CCF specimens to various compression cycles and testing temperatures, followed by a tensile capacity test. It was designed to evaluate the allowable extension in tension reported by the manufacturers for both room and elevated temperatures, and provide insight into the possible relationship between compression set and tensile failures. Any correlation (or lack of one) discovered between compression set and tensile capacity will help determine if, and to what degree, compression set is involved in the poor performance reported by many state agencies.

The results of the compression tests showed that the unrealistic compression cycle duration and testing temperature prescribed by the current ASTM standard do indeed produce compression set values that are too low. With all other parameters of the test remaining unchanged, specimens that experienced longer compression cycles exhibited a more than 100% increase in compression set, while those that experienced elevated testing temperatures exhibited a 300% increase. These drastically higher compression set values calculated from specimens that experienced more realistic testing conditions confirm the notion that the compression cycle and testing temperature from the current ASTM standard are not suitable for establishing the performance of these foams when used in bridge joints. However, these experiments were conducted with a consistent 24 hour rebound period. In the second experiment, the compression set of the same specimens were calculated over the course of 2 additional months. The results of these tests showed that for the room temperature specimens, after only a few weeks, the compression set naturally reduced to 4-5%, which is less than the commonly reported 9-10% by the manufacturers. The elevated temperature specimens also showed a natural reduction in compression set over longer rebound durations, but the lowest value calculated was 30%, which is still much greater than manufacturer's reported values. These results showed that a more realistic rebound period will also significantly improve the accuracy of the results, and that the current standard may not always be underreporting compression set. Specimens that have experienced elevated temperatures are still likely to have their compression set underreported by the current standard, but room temperature specimens may actually be underreported. The overall result from both of these tests is that testing conditions that better represent the in-service conditions are essential for accurately measuring compression set values in CCFs, and that the current ASTM standard yields values that are inappropriate for the bridge application, by reporting values that are either too high or too low depending on specific test parameters.

Among many other findings related to the tensile capacity of CCFs, the most important results from the third and final experiment were the extension measurements, used to calculate the percent elongation at failure. This data showed that while varied, the CCFs in this experiment consistently outperformed the 20-30% maximum elongation in tension reported by the manufacturer, with all maximum elongations lying in the 70-100% range. Compression set was instilled in these specimens by the compression cycles and testing temperatures, and its presence was confirmed by analyzing the curvature of the force-deflection curves. The existence of compression set and the lack of any poor tensile performance of the CCFs suggests that tensile capacity of foams that are appropriately bonded to the substrate are as-good or better than that reported by manufacturers, even in the presence of compression set of the foam.

However, the occurrence and the conditions that caused “foam body failures”, as described in chapter 3, raises an interesting point about the proper installation of CCFs. This specific type of failure was caused by a lack of careful adherence to the manufacturer’s installation procedures. While it is unlikely that this specific variety of failure is the sole cause of any widespread detriment, it does demonstrate the importance of a proper installation. Great care was taken in preparing the specimens that were tested in this experiment, and in turn, generally favorable performance occurred. The body failures observed in this experiment strongly suggest that the positive tensile performance of these tests were completely contingent on the proper installation that was ensured during the testing procedure. After becoming familiar with the challenges of the CCF adhering process through preparation of these tests, it seems likely that the necessary strict adherence to the installation procedures is not always occurring in the field. CCF material is installed into joints over great lengths, and into thicknesses that may not be conducive to proper procedure. These conditions make it difficult for contractors to properly apply the adhesive to the headers and the foam, and to insert the foam in such a way that maintains the proper amount and orientation of adhesive necessary to form a strong bond. The accumulation of excess adhesive that was shown to cause body failures also seems likely to occur during installation, when maintaining a clean working environment is a challenge. While this experiment successfully demonstrated that compression set is not a direct cause of tensile failure in CCFs, the behavior of these foams during the adhering process and while in tension revealed that a strict adherence to installation procedures is vital to the foam's performance in tension, and that a lack of such diligence may be the cause of the commonly reported failures.

The culmination of results from all three experiments conducted for this study contribute to two main findings. The first of these is the confirmation of suspicions that the current ASTM standard for determining compression set in CCFs is producing inaccurate estimations. The unrealistic values of compression cycle duration, testing temperature, and rebound period prescribed by the standard produce values of compression set that could be significantly higher or lower than what CCFs are likely to experience in the field. In order to predict compression set in CCFs to a higher degree of accuracy, the testing parameters of the current standard investigated in this study would have to be modified to more closely represent in-service conditions. The second main finding is that foam specimens tested in this study performed well in tension even when exposed to compression set, despite reports of poor tensile performance of foams in actual bridge joints. All specimens subjected to typical quantities of compression set were still able to perform above and beyond the tensile limits assigned by their manufacturers. The results of these tests however, were completely dependent on a strict adherence to the installation procedures provided by the manufacturer. The observed reliance of bond quality on proper installation techniques suggests that poor installation procedures are more likely to blame for tensile failures than the elastic properties lost to compression set. Ensuring the diligent and proper installation of CCFs during construction will create the most conducive conditions for reliable performance in tension.

The findings of this study suggest several recommendations for those involved with the design and maintenance of CCFs as they apply to bridge joints. If it is determined that the compression set of a foam product is vital to its performance, then the values reported by the manufacturer should be utilized very cautiously. Especially in locations where temperatures are expected to reach high levels (100-110oF) for sustained periods of time, more conservative values of compression set (30-35%) should be assumed, as opposed to values reported by manufacturers (9-10%) who test in accordance with the current ASTM standard. Since compression set was not able to be confirmed as the primary cause of reported CCF failures in tension, limiting their application to bridge joints that only experience compression is still a conservative method for ensuring positive performance. However, in situations where CCFs are expected to perform in tension, a greater emphasis must be placed on proper installation. Tensile performance is completely reliant on a strong bond, which requires a strict adherence to the prescribed installation procedures. Investing more time and effort into the installation process will have the greatest effect on ensuring the reliable performance of a CCF in tension.

REFERENCES

AASHTO (2007). *LRFD Bridge Design Specifications - SI Units (4th Edition)*. American Association of State Highway and Transportation Officials, Washington, D.C.

Almanza, O., Y. Masso-Moreu, N. J. Mills, and M. A. Rodríguez-Pérez. "Thermal Expansion Coefficient and Bulk Modulus of Polyethylene Closed-cell Foams." J. Polym. Sci. B Polym. Phys. Journal of Polymer Science Part B: Polymer Physics 42.20 (2004): 3741-749. Web.

Almanza, O., M. A. Rodríguez-Pérez, and J. A. De Saja. "Measurement of the thermal diffusivity and specific heat capacity of polyethylene foams using the transient plane source technique." *Polymer international* 53.12 (2004): 2038-2044. Web. 7 Jan. 2016.

Arizona Department of Transportation (2001). *ADOT Bridge Design Guidelines*. Arizona Department of Transportation, Phoenix, AZ. (Section 14)

ASTM Standard D3575-14, 20XX, "Standard Test Methods for Flexible Cellular Materials Made From Olefin Polymers," ASTM International, West Conshohocken, PA, 2014, DOI: 10.1520/D3575, www.astm.org.

"Average Weather For Phoenix, Arizona, USA." WeatherSpark Beta. Cedar Lake Ventures, Inc, n.d. Web. 27 Jan. 2015. <https://weatherspark.com/averages/30435/Phoenix-Arizona-United-States>.

Burke, Martin P. (1989) NCHRP Synthesis of Highway Practice 141: Bridge Deck Joints. September, 1989. Transportation Research Board, National Research Council. Washington, D.C.

Dahir, Sabir H. and Mellott, D.B. (1987), "Bridge Deck Expansion Joints" Transportation research record 1987: 16-24. Transportation Research Board, Washington, DC

Gibson, L. J. Proceedings of the Royal Society of London. Series A, Mathematical and Physical Sciences: MECHANICS OF THREE-DIMENSIONAL CELLULAR MATERIALS. 382 Vol. Harrison and Son, 1982. Web. 6 Jan. 2016.

Milner, M.H. and Shenton III, H.W. (2014), "Survey of Past Experience and State-of-the-Practice in the Design and Maintenance of Small Movement Expansion Joints in the Northeast," AASHTO Transportation System Preservation Technical Services Program (TSP2); http://sites.udel.edu/dct/research/publications/soils-structures-and-bridges/

Purvis, Ron. (2003) NCHRP Synthesis of Highway Practice 319: Bridge Deck Joint Performance. Transportation Research Board, National Research Council. Washington, D.C.

Sims, G.L.A. (1997). "Initial impact studies on open and closed-cell foams". Cellular polymers (0262-4893), 16 (6), p. 431. Web. 6 Jan. 2016.

Stovall, Therese, M. Vanderlen, and J. Atchley. "Closed cell foam insulation: a review of long term thermal performance research." Final report, ORNL/TM-2012/214. 2012. Web. 7 Jan. 2016.

Texas Department of Transportation (2013). *Bridge Design Manual-LRFD.* Texas Department of Transportation, Austin, TX. (Chapter 3, Section 2)

Weykamp, Peter. 2014. Personal Communication.

Xu, Tao. Composites. Part A, Applied Science and Manufacturing: Effects of Ultraviolet Radiation on Morphology and Thermo-Mechanical Properties of Shape Memory Polymer Based Syntactic Foam. 42 Vol. Elsevier, 2011. Web. 6 Jan. 2016.

Appendix A

ASTM D3575 EXCERPT

8. Measurement of Test Specimens

8.1 Measure dimensions up to and including 25.4 mm (1 in.) using a dial-type gauge with a minimum foot area of 645.1 mm^2 (1 $in.^2$). Pressure on the foot shall be held to 190 ± 50 Pa (0.028 ± 0.007 psi).

NOTE 2—Where foam is appreciably compressed by this test method, foot area and loading shall be as agreed upon between the purchaser and the supplier.

NOTE 3—Thickness of materials having irregular surface characteristics shall be measured as agreed upon between the purchaser and the supplier.

8.2 Dimensions over 25.4 mm (1 in.) may be measured with a dial gauge, scale, or tape. Take care not to distort the test specimen.

8.3 The scale, tape, or gauge shall be graduated to permit measurements within ±1 % of the dimension to be measured.

8.4 Results reported shall be the average of a minimum of three equally spaced measurements of length and width and for thickness shall be the average of the center and four equally spaced measurements around the perimeter of the specimens.

Suffix Tests Suffix B—Compression Set Under Constant Deflection

9. Scope

9.1 This test method covers the deflection of the foam specimen under a compressive force and under specified conditions of time and temperature, then noting the effect on the thickness of the specimen after releasing the compressive force.

10. Apparatus

10.1 *Compression Device*, consisting of two or more flat steel or aluminum plates that are of sufficient thickness to prevent deflection of the plates under load. The plates are held parallel to each other by bolts or clamps, and the space between the plates is adjustable to the required deflection thickness by means of spacers.

11. Test Specimens

11.1 The test specimens shall have parallel top and bottom surfaces and essentially perpendicular sides.

11.2 Specimens shall be 50.8 by 50.8 by 25.4 mm (2 by 2 by 1 in.) unless otherwise specified. Specimens less than 25.4 mm in thickness shall be plied up, without the use of an adhesive, to produce a total thickness of 25.4 mm.

NOTE 4—To obtain accurate data when testing foams with large cells or irregular surfaces, or both, larger samples approximately 101.6 by 101.6 by 25.4 mm (4 by 4 by 1 in.) are recommended.

12. Number of Specimens

12.1 Test three specimens for each sample. The values reported shall be the mean of those observed. If any value deviates more than 20 % from this mean, test two additional specimens and report the mean for all five values.

13. Procedure

13.1 Perform the entire test procedure at 23 ± 2°C (73.4 ± 3.6°F).

NOTE 5—See Practice D1349 if conditions other than these are desired.

13.2 Measure the test specimen original thickness (t_o) in accordance with the procedure in Section 8.

13.3 Place the test specimen or specimens in the apparatus in a manner that will not allow the specimens to come into contact with each other upon being compressed and deflect the specimens to 50 % ± 1 % of their thickness.

13.4 Allow the test specimen to remain deflected in the apparatus for 22 h ± 30 minutes.

13.5 Remove the specimen from the test apparatus at the end of the 22-h period. Measure the final thickness (t_f) after 24 h ± 30 minutes of recovery.

14. Calculation

14.1 Calculate the constant deflection compression set, expressed as a percentage of the original thickness, as follows:

$$C_d = \frac{(t_o - t_f)}{t_o} \times 100 \quad (1)$$

where:

C_d = compression set expressed as a percent of the original thickness,
t_o = original thickness, mm (in.), and
t_f = thickness of the specimen after the specified recovery period, mm. (in.)

15. Report

15.1 Report the average compression set value, of the three specimens tested, for each sample, except as noted in 13.1.

Appendix B

COMPRESSION SET TESTING TEMPERATURE DATA

B.1 T_{max} Values for Thermal Expansion Design Considerations

B.1.1 AASHTO LRFD Bridge Design Manual

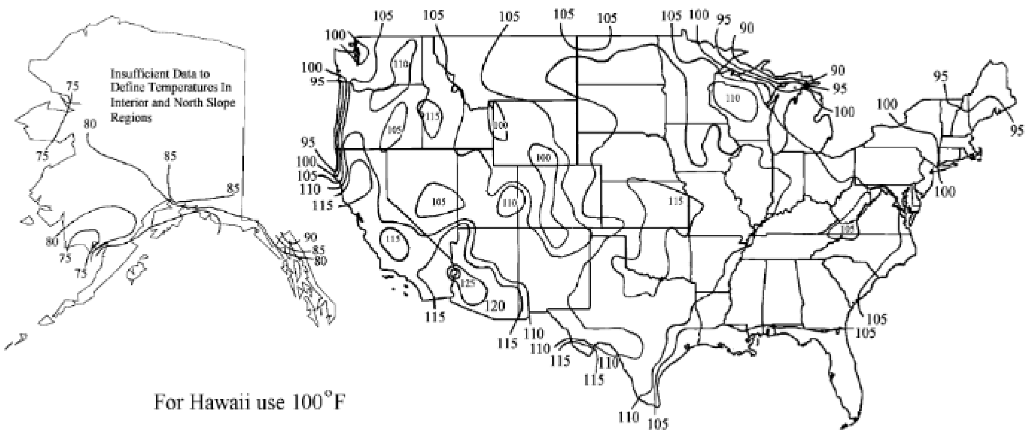


Figure 3.12.2.2-1—Contour Maps for $T_{MaxDesign}$ for Concrete Girder Bridges with Concrete Decks

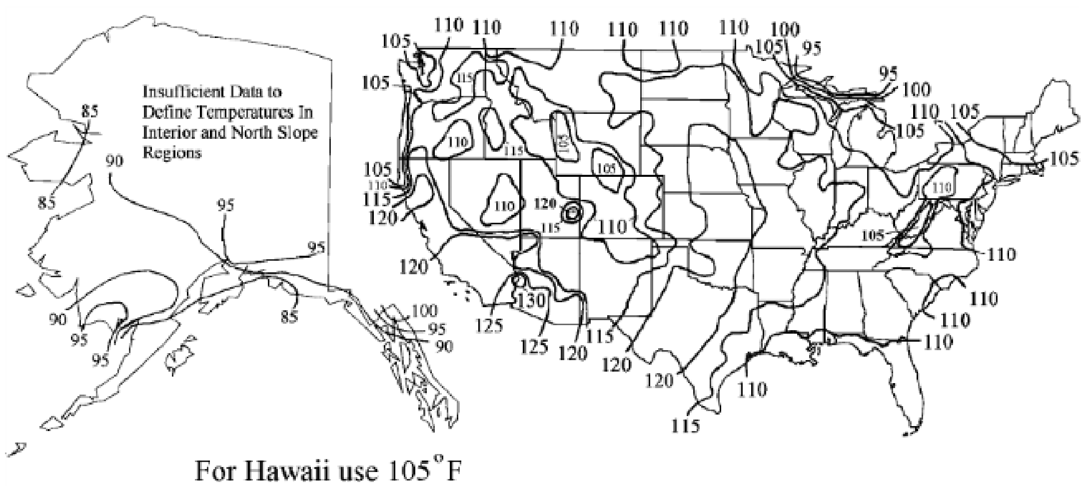


Figure 3.12.2.2-3—Contour Maps for $T_{MaxDesign}$ for Steel Girder Bridges with Concrete Decks

B.1.2 Texas Department of Transportation Bridge Design Manual

Structural Analysis

Assume a temperature change of 70 degrees Fahrenheit after erection when calculating thermal movement in one direction (not total). Take T_{min} = 10 degrees F and T_{max} = 80 degrees F. For the panhandle region use T_{min} = 10 degrees F and T_{max} = 115 degrees F, for a total temperature change of 105 degrees F.

B.1.3 Arizona Department of Transportation Bridge Design Manual

ADOT Bridge Design Guidelines 14-3

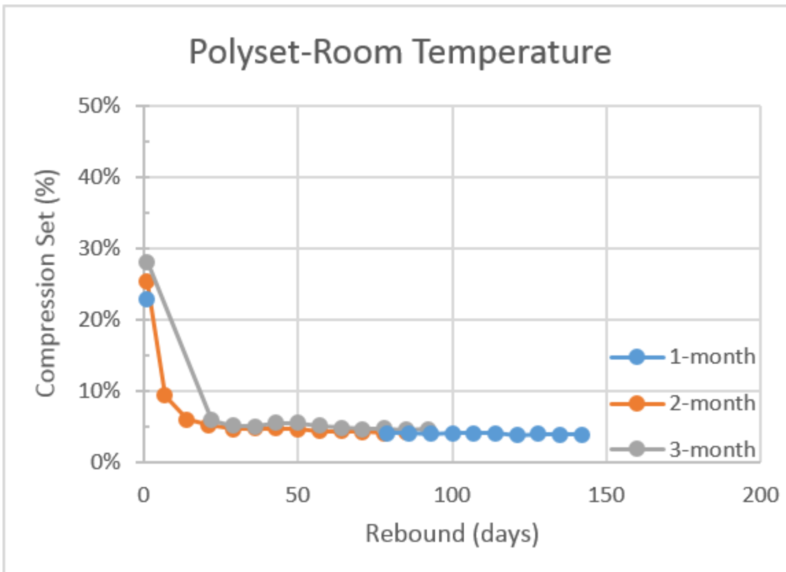
		Concrete		Steel	
Elevation (ft)	Mean (°F)	T_{min} (°F)	T_{max} (°F)	T_{min} (°F)	T_{max} (°F)
Up to 3000	75	35	105	15	135
3000 - 6000	60	20	90	0	120
Over 6000	50	5	85	-30	120

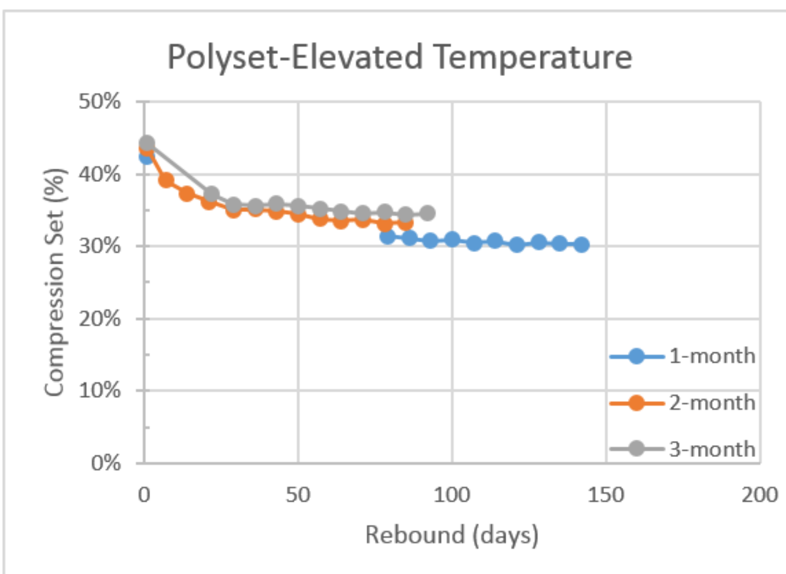
Appendix C

REBOUND TEST RESULTS

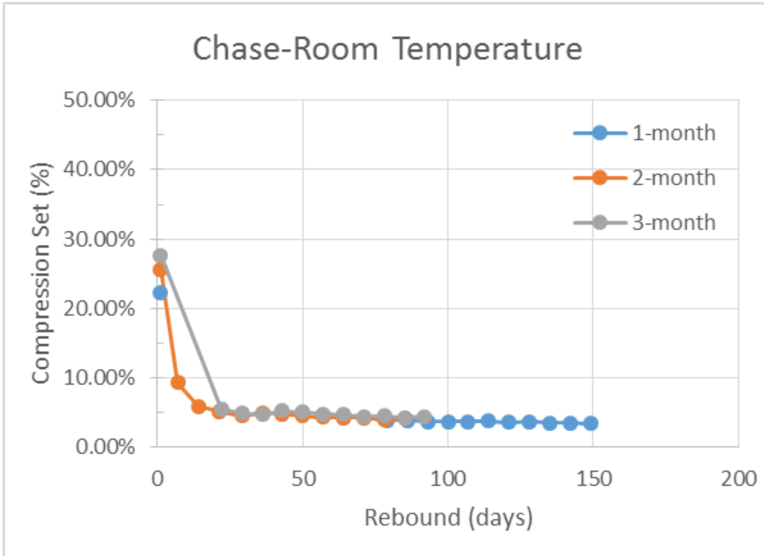
C.1 Room and Elevated Temperature Results

C.1.1 Polyset

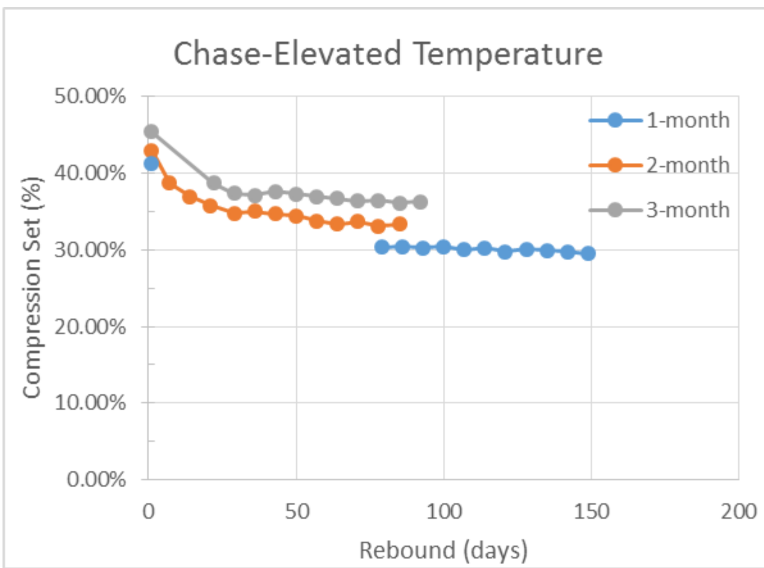




C.1.2 Chase

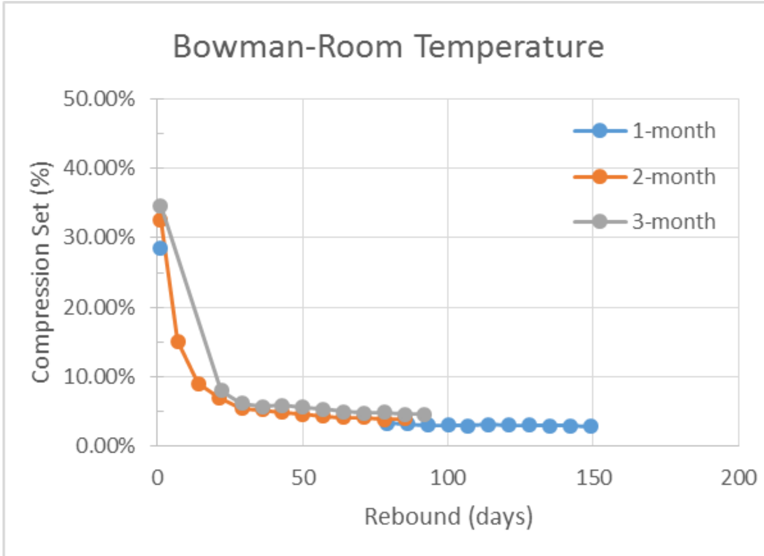


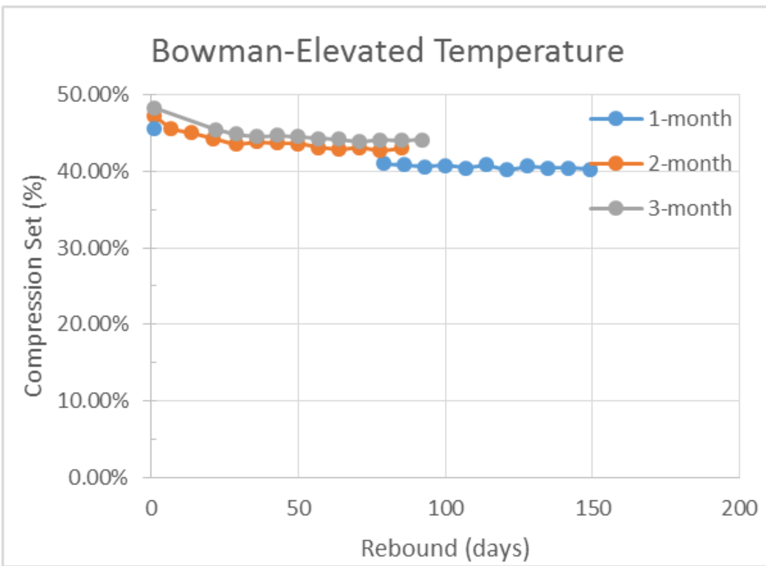
Chase-Room Temperature
50.00%
40.00%
30.00%
20.00%
10.00%
0.00%
Compression Set (%)
0
50
100
150
200
Rebound (days)
1-month
2-month
3-month



Chase-Elevated Temperature
50.00%
40.00%
30.00%
20.00%
10.00%
0.00%
Compression Set (%)
0
50
100
150
200
Rebound (days)
1-month
2-month
3-month

C.1.3 Watson Bowman Acme





C.1.4 R J Watson