TEST METHODS FOR ELASTOMERIC
BEARINGS ON BRIDGES

by

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To my beloved parents and sisters

for their continuous love, encouragement, and support.

ABSTRACT

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Elastomeric bearing pads are used extensively in bridge structures. Whereas, the mechanical properties of elastomers like Young's modulus, compressive modulus, and shear modulus are usually essential for the structural engineer's work, most rubber manufacturers describe their products in terms of chemical compounds, hardness, tensile stress at some elongation, and compressive set measurements in order to meet AASHTO material specifications. This paper discusses the material properties of elastomers and the factors that influence these properties. The development of the AASHTO specifications between 1961 and 1992 on elastomeric bearings are also summarized. In addition, various sizes of bonded natural rubber blocks were tested in compression, tension, shear, and combined compression and shear. Load deformation relationships were obtained from all tests and mechanical properties of compressive modulus, tensile modulus, and shear modulus were calculated. Test results indicated that specimen size affects the material properties of an elastomer. Furthermore, the measured shear modulus values were not affected by various levels of compressive stress.

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CHAPTER 1
INTRODUCTION

This study is part of a larger research project sponsored by the Texas Department of Transportation, TxDOT, entitled "Elastomeric Bearings." The project was funded to study the behavior and performance of elastomeric bridge bearings and to recommend practical design procedures for the TxDOT. The research was partitioned into several tasks, namely, field surveys, basic material tests, development of engineering models, and design procedures. This study falls under the basic material tests portion and concentrates on the mechanical properties of elastomers, mainly natural rubber. The project was conducted at the Phil M. Ferguson Structural Engineering Laboratory, FSEL, of the University of Texas at Austin, UT.

1.1 Problem Statement

The current AASHTO specification (1) allows the structural engineer to design elastomeric bridge bearings, both plain and steel laminated, based on their Durometer Shore A hardness or on their material property of shear modulus, G. Specifying an elastomer by its hardness is simply a matter of convenience since such a test is popular for its quickness and simplicity. However, it is worthwhile mentioning that the hardness test is sensitive to the way the operator uses the instrument as well as to the thickness of the sample. Whereas the hardness test is simple, easy, and convenient, it may not provide an adequate measure of the mechanical properties of the elastomer. Moreover, the relationship between shear modulus and hardness is not clearly defined and previously conducted studies show a lot of scatter between these two properties.

The shear modulus, on the other hand, is a very important mechanical property of an elastomer since it directly enters in the design equations of the AASHTO specifications for elastomeric bearings (1). The AASHTO specifications strongly recommend that the bearing pad be fabricated based on a specified shear modulus, rather than durometer hardness. Nevertheless, the method of obtaining a certain mechanical property, say Young's modulus, E, or G, the type of tests that should be performed to verify such properties, and the acceptable percent deviation from the required values are not well documented.

In addition, E is considered to be three times that of G based on a Poisson's ratio, ν, for rubber of approximately 0.5. However, this ratio is known to change from one elastomer to another. Since the AASHTO specification replaces E with 3G in all its design equations, this creates a problem and further investigation into this relationship is necessary.

1.2 Purpose of Study

The author intends to supply the engineer with a solid background concerning the mechanics and behavior of elastomers that are relevant to the design of elastomeric bridge bearings. The mechanical properties of elastomers that structural engineers are interested in will be addressed and the capabilities of rubber technologists to manipulate these properties by varying chemical ingredients will be emphasized. Most importantly, terminology used by both parties will be explained. Next, the author will clarify some of the relationships between the various material and physical properties of the elastomer such as durometer hardness, E, compressive modulus, E_c, and G. Finally, an experimental study was conducted to compare the shear modulus values obtained from the tests with the nominal shear modulus values ordered from the supplier. Furthermore, the effect of compressive stress on the behavior of the rubber block in shear as well as the effect of specimen size on the calculated material properties of the elastomer will be investigated.

1.3 Scope of Tests

Static tests in compression, tension, shear, and combined compression and shear on rubber blocks comprise the experimental program presented in chapter four of this thesis. Tests were carried out at room temperature on bonded natural rubber specimens that varied in sizes of 4 x 4 x 1 in. (101.6 x 101.6 x 25.4 mm) and 2 x 2 x 0.5 in. (50.8 x 50.8 x 12.7 mm) and nominal shear moduli, G_n, of 100psi (0.69MPa), and 200psi (1.379MPa). Load deformation relationships were obtained from all tests and mechanical properties such as E_c, tensile modulus, E_t, and G values were determined.

CHAPTER 2
BACKGROUND

The starting material for the production of elastomers or rubbers is caoutchouc. Caoutchouc, derived from the Indian word "Caa-o-chu", or "weeping tree", is polyisoprene, $(C_5H_8)_n$, which is recovered from the sap of the rubber tree, *Hevea Brasiliensis* (2). This material is referred to as natural rubber, NR. After undergoing chemical compounding at elevated temperatures, NR is transformed from a sticky and highly plastic state (caouchouc or raw rubber) to an elastic one (elastomer or rubber). In the recent years a large number of synthetic rubbers, SR, with a wide variety of chemical compositions have been developed. Polystyrene, polychloroprene "Neoprene", and polytetrafluoroethylene "Teflon", among others, are examples of SR.

2.1 Rubber as an Engineering Material

The effective use of rubber as an engineering material depends on the understanding of its behavior and chemical composition. It is necessary to recognize that an elastomer is a simple elastic material in the same sense that the steel is elastic, although it is much softer. Its ability to function as a soft compact spring is one of the main reasons for its wide use (3). Elastomers, which are produced by a complex chemical reaction during processing and usually containing many additives, are not perfectly reproducible. This explains why the elastic moduli vary by a few percent for nominally identical rubbers (3). In the civil engineering industry, elastomers are mainly used in bridge bearings and base isolation bearings for buildings subjected to earthquakes.

2.1.1 Manufacture and Chemical Composition: Rubber manufacture usually consists of three basic stages, namely, compounding, processing, and vulcanization.

<u>2.1.1.1</u> <u>Compounding:</u> The compounding stage consists of the proportioning of raw rubber material with the vulcanization chemicals. The raw rubber material can either be natural or synthetic and usually constitutes the largest percentage of the compounding ingredient. The vulcanization chemicals are numerous and each one serves a specific purpose as explained below.

Crosslinking Agents: During the vulcanization stage, the crosslinking agents combine with the raw rubber monomer or single molecule (e.g. isoprene "C_5H_8") to form a polymer or chain of molecules (e.g. polyisoprene "$(C_5H_8)_n$"). Sulphur, peroxide or urethane are typical crosslinking agents.

Accelerators: They are used in conjunction with the crosslinking agents to control the crosslinking density. For lower sulphur concentrations, larger amounts of accelerators are required.

Metal Oxides: They are required in a compound to develop the full potential of accelerators. The main metal oxide is zinc oxide, but other oxides are used at times to achieve specific results.

Activators: Many accelerator systems require additional activators, like fatty acids, zinc soaps, or amine stearates.

Vulcanization Inhibitors: Chemicals like phthalimide sulfenamides are needed to prevent premature vulcanization or scorching of the elastomer.

Protective Agents: Because it is highly unsaturated, NR has to be compounded with protective agents to achieve a sufficient aging resistance. The level of protection is determined by the chemical nature of the protective agent. Most effective are aromatic amines, such as p-phenylene diamine derivatives, which not only protect the vulcanizate against oxidative degradation, but also against dynamic fatigue and degradation from ozone and heat. For ozone protection, one uses waxes in combination with p-phenylene diamine in dark-colored vulcanizates, or with enol ethers in light colored ones.

Fillers: Contrary to most types of SR, NR does not require the use of fillers to obtain high tensile strengths. However, the use of fillers is necessary in order to achieve the level and range of properties that are required for technical reasons. Carbon black is the filler typically used in elastomeric bearings. It is added to modify the hardness and adjust the stiffness of the rubber. The filler also affects the tensile strength, elongation at break, creep, and stress relaxation (4).

Softeners: A great number of different materials serve as softeners, the most important ones being mineral oils. Animal and vegetable oils are also important softeners. NR requires lesser amounts of softener than most SRs.

Process Aids: Stearic acid, zinc and calcium soaps, and residues of fatty alcohols are some process aids which are used in NR compounds in addition to softeners. These materials are important since they facilitate the dispersion of fillers in the rubber compounds and they ensure smooth processing.

2.1.1.2 Processing: Rubber processing consists of two steps, namely mastication and mixing. Unless NR has been modified by the producer to a specific processing viscosity, it is very tough and therefore requires mastication prior to compounding. During mastication, the NR molecules are mechanically broken down by means of high shear forces. Mastication can be carried out on mills at low temperatures or at elevated temperatures in the presence of peptizing agents.

Mixing can be performed either on mixing mills or in internal mixers. When mixed in an open mill, the rubber is first worked on the mill until a coherent band is formed on the mill rolls (see Figure 2.1). Subsequently, protective agents and accelerators are added so that they will be well dispersed during the mixing cycle (see Figure 2.2). Next, part of the filler is added together with stearic acid (see Figure 2.3). When adding softeners, the band will split and it has to heal before additional fillers are added to the compound. Finally, the sulphur is mixed in. During the mixing process, the band must not be cut, and only after all ingredients have been incorporated in the compound, is the band cut and folded (see Figure 2.4). When the mixing cycle is completed, the compound is cut from the mill as slabs and cooled in a water bath and stored. Since mixing on mills is very time consuming, mixing in internal mixers is preferred.

Figure 2.1 Rubber is Worked on the Mixing Mill

Figure 2.2 Chemical Ingredients are Added to the Rubber Band

Figure 2.3 Carbon Black Filler is Added to the Rubber Band

Figure 2.4 The Rubber Band is Cut From the Mill

When mixing is carried out in internal mixers, a relatively hard rubber is required for good and efficient dispersion of the compounding ingredient. The usual mixing temperatures are 284-302^{o}F (140-150^{o}C). When mixing NR compounds in internal mixers, the rubber is first added followed by fillers, while with high mixing temperatures, it is necessary to add accelerators later on in a separate mixing pass. Sulphur and accelerators are either added together after the compound has cooled down, or separately on a mill after the compound has warmed up again. After mixing, the compound is dumped from the internal mixer onto a cooling mill. It is then cut into slabs and allowed to cool. At this stage, the rubber has a texture similar to a soft taffy candy. It is maintained in this state in a controlled temperature and humidity room until vulcanization into its final hard form (see Figure 2.5).

2.1.1.3 Vulcanization: The necessary crosslinkages between molecules are normally introduced in the process of vulcanization. They are due to a chemical reaction between the rubber and the sulphur and are as strong as the primary bonds in the chain itself. Figure 2.6 shows the difference between a non-crosslinked rubber (plastomer) and a cross-linked rubber (elastomer).

Figure 2.5 Slabs of Rubber are Stored in a Controlled Temperature and Humidity

Figure 2.6 Rubber Before and After Vulcanization (2)

In natural rubber and some synthetic rubbers (e.g. Neoprene), the vulcanization reaction is possible because of the highly reactive double bonds in the polyisoprene and polychloroprene chains (Figure 2.7).

Figure 2.7 Structural Formulas of Polyisoprene and Polychloroprene (40)

The vulcanization or curing of the compounded rubber is usually carried out under pressure in metal molds at a temperature of about 284^{o}F (140^{o}C) and takes from a few minutes to several hours depending on the type of vulcanization system being used and the size of the component. The finished component has the shape of the mold cavity.

2.1.2 Rubber Compared to Metals: The elastic behavior of rubber differs fundamentally from that of metals (3). In metals, deformation consists of changes in the inter-atomic distances. Since very large forces are required to change these distances, the elastic modulus of metals is very high. The forces are so great that before the deformation reaches a few percent, slippage between adjacent metal crystals takes place. The metal shows a yield point above which the deformation increases rapidly with small increases in stress. From this point on, the deformation is irreversible or plastic (see Figure 2.8, curves C and D).

With rubber, on the other hand, the stress-strain curve (A) bends the other way and no "yield point" exists. The rubber recovers most of its deformation from any point on the stress-strain curve (see Figure 2.8, curve B). The deformation of rubber consists of the uncoiling of the elastomeric chains as compared to the straining of the inter-atomic bonds in metals. Since the forces required are much smaller than the ones present in metals, the elastic modulus of rubber is very low.

Poisson's ratio applies to both metals and rubber. Nevertheless, it is important to know that the nearness of Poisson's ratio to 0.5 makes rubber virtually incompressible. The Poisson's ratio for metals is normally between 1/4 and 1/3.

Unlike metal hardness, which is measured by irreversible plastic indentation, elastomer hardness is measured by reversible elastic indentation under a steel point. The hardness of an elastomer is typically measured with an instrument called durometer (Shore A).

Figure 2.8 Stress-Strain Curves for Loading and Unloading of Rubber and Metals (3)

2.1.3 Behavior of Rubber:

2.1.3.1 Creep, Relaxation and Energy Loss: Elastomers are unique materials due to the fact that they are capable of storing and dissipating energy via their characteristic large strain behavior (1). Their ability to do so characterizes them as viscoelastic materials. Since they are not truly elastic in terms of Hooke's law, viscoelastic materials (e.g. rubbers) undergo two types of relaxation, namely, strain relaxation (creep) and stress relaxation (see Figure 2.9). In elastomers, stress relaxation is a chemical reaction caused by the breaking of primary chemical bonds (5), whereas, creep is due to an internal reorganization of molecules within the elastomer (6). While stress relaxation results from constant strain on the elastomer, creep or strain relaxation is caused by constant stress.

Creep changes exponentially with time being most rapid immediately after the application of the load and diminishing thereafter. The magnitude of creep depends on the composition of the elastomer and type of stress applied. For example, creep under tensile stress is about 50% higher, and under shear stress about 25% higher than creep under compressive stress (6). The relaxation rate of all natural rubber vulcanizates is generally lower than that of other rubbers (7).

Hysteresis, a measure of energy loss, is the work represented by the area between the loading and unloading curves in a loading-deformation cycle (see Figure 2.10). Hysteresis depends not only on the type of the elastomer but also on the compounding ingredients (7) (e.g. fillers increase hysteresis).

Figure 2.9 Stress and Strain (creep) Relaxation in Elastomers (5)

Figure 2.10 Typical Stress-Strain Loading-Unloading Cycle of Rubber (8)

2.1.3.2 Compression, Tension, and Shear: Elastomers behave differently in compression, tension, and shear. Figure 2.11 shows typical stress-strain curves of rubber in compression and shear. It is obvious that the stress-strain relationship in shear is linear whereas that in compression is not. This is due to the fact that the rubber bulges at its sides when compressed. Figure 2.11 also indicates that shear strains up to unity are possible while compression strains can never reach unity (3).

Figure 2.11 Comparison of Stress-Strain Curves of Rubber in Compression and Shear (3)

A typical tensile stress-strain curve for rubber is shown in Figure 2.12. It can be seen that there is no linear elastic portion as is usual with metals (also see Figure 2.8). In order to get a measurement of Young's modulus, an early part of the tensile stress-strain curve (e.g. between 0.05 and 0.10 strains) should be considered.

Figure 2.12 Tensile Stress-Strain Curve for Rubber (9)

2.2 Elastomeric Bridge Bearings

The most common type of structural bearing used on highway bridges is the elastomeric bearing. The prime function of elastomeric bearings is to protect the structures when relative movements occur between adjacent structural members by preventing the transmission of harmful forces, bending moments and vibrations (10). Elastomeric bearings have three important advantages over conventional sliding plates, rocker arms and rollers used to support bridge girders. Such bearings are economical, effective, and require no maintenance (11). Compared to the average mechanical bearing, an elastomeric bearing is more economical because of its simple design, ease of construction, and low material costs. For example, a 9 x 22 x 3in (23 x 56 x 8cm) elastomeric bearing costs between $60 and $80. An important quality of the elastomeric bearing is its effectiveness as a medium of load transfer (11). When subjected to compression forces, the bearing pad absorbs surface irregularities. When subjected to horizontal forces caused by the expansion and contraction of the bridge girders, the bearing deflects to accommodate these deflections. Finally, an elastomeric bearing needs no maintenance since it does not require lubrication or cleaning.

Elastomeric bearings come in two types: plain (unreinforced) pads that are simple rectangular blocks of rubber (Figure 2.13a) and laminated (reinforced) pads that have thin horizontal steel plates embedded at specific intervals within the elastomer (Figure 2.13b). Both reinforced and unreinforced bearings accommodate longitudinal movements of the bridge by simple shear deformation (Figure 2.13c). Shear deformations as large as the rubber thickness are possible, nevertheless, it is common practice to limit this deformation to half this value. Once the horizontal deflections of the bridge are known, the thickness of the rubber can be chosen.

A plain pad behaves differently from a reinforced bearing when subjected to a compressive force. This difference has to do with the amount of bulging that is taking place around the bearing as well as the amount of vertical deformation. The presence of steel laminates drastically reduce the bulging effect and the amount of vertical deformation (Figures 2.13d, and 2.13e). One can control the bulging pattern by controlling the shape of the bearing, namely, the elastomer thickness between steel laminates and the cross-sectional area. This influence of shape may be numerically expressed as the "shape factor, S" (11). This value is defined as the ratio of the loaded area to the surface area that is free to bulge. For a rectangular bearing with length L, width W, and layer thickness t, $S=LW/2t(L+W)$, and for a circular bearing with diameter d, $S=d/4t$. While the addition of layers of reinforcement can reduce the vertical deflection and bulging pattern, it does not stiffen the bearing in shear (12).

Figure 2.13 Plain and Reinforced Elastomeric Bearings

2.2.1 Failure Modes: Reasons and Remedies: The failure modes for elastomeric bearings are failure of the reinforcement in tension, debonding at the rubber/steel interface, non-uniform bulging of the elastomeric pad, and slipping (12, 13, 14). When a reinforced bearing is loaded in compression, the reinforcement restrains the bulging of the elastomer and in turn develops large tensile stress. This failure can be eliminated by reducing the compressive forces on the bearing or selecting thicker steel plates. Maximum shear stress due to compression occurs between the elastomer and the reinforcement interface. When the bond is not as strong as the parent elastomer, debonding is likely to occur. This can be prevented by making sure that the reinforcement is properly cleaned and primed before the bearing is vulcanized by the manufacturer. Non-uniform bulging of the laminated bearing takes place when the reinforcement is not properly distributed or placed in the bearing. Such a failure is usually attributed to the lack of manufacturing and processing control in the production of the bearings (13).

Elastomeric bearings are usually designed to accommodate compressive and shearing forces by simple deformation. When the horizontal applied forces are higher than the frictional forces between the elastomer/steel or elastomer/concrete interface, the bearing will most likely start to slip. A one time slip upon the installation of the elastomeric pad on the bridge abutment is acceptable, however, repeated slip backwards and forwards may cause abrasion of the elastomer to take place and thus damage the elastomer surface that is in contact with the steel or concrete surface. The slip phenomenon is more common in plain bearings than laminated ones. In laminated bearings, the elastomer is sandwiched between two steel plates which in turn reduce the amount of bulging and absorb the stresses that are developed in the elastomer. In the case of plain bearings, the amount of bulging is bigger and the stresses developed in the rubber have to be resisted by the frictional forces between the bearing and the abutment interface. Since the tensile forces are higher at the bearing's edges, slip will take place near the edges of the bearing and not in the center (see Figure 2.14a). Some engineers, in order to prevent this slipping phenomenon recommend that all layers of elastomer should be bonded between steel plates (6). The outermost steel plates should be covered by only a thin layer of elastomer to prevent corrosion of the reinforcement (see Figure 2.14b).

Figure 2.14 Slip Phenomenon in Plain and Reinforced Bearings

2.3 Structural Engineer and Rubber Technologist

References 14 and 15 discuss the differences between structural engineers and rubber technologists in terms of their understanding of elastomeric bearings. Elastomeric bearings are usually designed by structural engineers who possess a very good understanding of the load-deformation capacity of the structure but have very little understanding of the behavior of the elastomer or the mechanics of the bearing. Engineers have to understand that elastomers behave differently than traditional materials, concrete or steel, when used to transfer loads and accommodate movements between the bridge superstructure and its supporting structure. On the other hand, a rubber technologist, who is really a chemist, usually supervises the chemical compounding and manufacturing processes of elastomeric bearings without having any knowledge of the structural requirements. At the same time that the structural engineer believes that the elastomer can accommodate a little more load or deformation, the rubber manufacturer believes that his rubber compound, or manufacturing methods and tolerances have no effect on the structure or on the behavior of the elastomeric bearing.

2.3.1 Terminology and Importance of Communication: References 3, 5, and 9 emphasize the importance of good communication and terminology between the structural engineer and the rubber technologist in order for the elastomer to be used effectively. If the structural engineer has some knowledge and understanding of the elastomeric material, his demands on the rubber technologist may be more realistic and the final design will be more satisfactory. Similarly, the rubber technologist needs to have some understanding of the structural requirements of elastomeric bearings in addition to his solid background in the chemical compounding and behavior of elastomers.

Since both the rubber technologist and structural engineer work under different disciplines, the terminology common to one might mean something else to another. For example, to the structural engineer, the word "modulus" means either Young's modulus, E, or shear modulus, G, whereas to the some rubber technologists, the same term stands for the tensile stress value at an arbitrary elongation, (100%, 200%, or 300%). The term "flexure" to an engineer means "bending", whereas to some rubber technologists it means "any form of straining". Similarly, the term "ageing in steel" to an engineer means "stress relieving before final machining", while to a rubber technologist it means "deterioration with age".

2.3.2 Design Needs of the Structural Engineer: When designing an elastomeric pad, a structural engineer is interested in a bearing that can resist the vertical forces resulting from the weight of the slab and beam as well as the moving traffic above. The amount of vertical deflection should be minimal. In addition, the bearing should be able to deform horizontally in order to accommodate the expansion and contraction of the precast concrete or steel beams due to temperature changes.

One can control the behavior of an elastomeric pad by controlling its mechanical properties, namely, the compressive modulus, E_c, G. A compressive value of infinity and shear modulus of zero would be ideal for an elastomeric bearing, nevertheless, such values are impossible to obtain. For a pad that has a constant elastomer thickness, the compressive modulus can be varied by controlling the amount of bulging that takes place (i.e. changing the shape factor). This can be accomplished by inserting a number of thin steel plates in the elastomer. By increasing the compressive modulus, the amount of bulging is lowered and the vertical deflection is decreased. Even though the compressive modulus can be increased by inserting steel plates, the shear modulus can be held constant by not changing the total thickness of the elastomeric material.

Another way that an engineer can vary the shear modulus and compressive modulus values is by using elastomers of various hardnesses. The most common hardness values used for elastomeric bearings are 50, 60, and 70 durometer. Elastomers of 50 durometer have lower compressive and shear modulus values than 70 durometer hard elastomers. The hardness of an elastomer can be controlled by the rubber technologist who can vary the chemical compounding ingredients that go into the manufacture of rubber.

2.3.3 Mix Proportioning Abilities of the Rubber Technologist: In section 2.1.1.1, it was shown that various chemical ingredients go into the chemical composition of an elastomer. The rubber technologist can basically formulate any type of elastomer that will meet the customer's requirements. When it comes to elastomeric bearings, the civil engineer's requirements include mechanical properties such as shear and compressive moduli, and physical properties such as hardness and ozone/age resistance. The rubber technologist can improve the age resistance of an elastomer by increasing the amount of metal oxides (e.g. zinc oxide) (16). Higher amounts of waxes will improve the ozone resistance. The most important ingredient that affects the mechanical properties of an elastomer is the amount and type of filler used. The typical filler used in the manufacture of elastomeric bearings is carbon black. Adding more carbon black will increase the hardness of the elastomer, increase the shear and compressive moduli, and decrease the elongation at break (13). Furthermore, the rubber technologist can vary the modulus of the elastomeric material by controlling the time of vulcanization. Figure 2.14 shows the effect of the vulcanization time on the tensile strength and modulus of a typical NR material. The hardness of the elastomer can be controlled to ±5 durometer units, and the shear modulus to ±10%.

Figure 2.15 Effect of Vulcanization Time on the Tensile Strength and Modulus of NR (8)

2.4 Summary of the AASHTO Specification Changes

The American Association of State Highway and Transportation Officials, AASHTO, specifications on the design and construction of elastomeric bearings have changed considerably from the time that they were first introduced in the early 1950's. The author will summarize the most important changes and additions made to AASHTO specifications starting with the 8th edition (1961) up to the 15th edition (1992).

In section 1.6.47 of the 8th edition (1961) of the AASHTO specifications (17), entitled "Expansion Bearings", the design requirements for elastomeric bearings were discussed. The specifications limited the maximum horizontal displacement of a bearing to half the thickness of the elastomer. The compressive stress was limited to 500psi (3.45MPa) for dead load and 800psi (5.52MPa) for combined dead and live load. The maximum allowable compressive deflection was limited to 15 percent of the elastomer thickness. The taper in the bearing was restricted to 5 percent of the pad length and to take care of stability requirements, the least dimension of the bearing had to be at least five times the thickness of the elastomer. All bearings were required to have a shape factor of 1.25, made of a material known as "Neoprene" and cast in molds under heat and pressure. The chemical composition for all pads had to meet the American Society for Testing and Materials, ASTM, requirements given in Table 2.1.

The only change in the 9th edition (1965) of the AASHTO specification (18) was that pads had to be secured against horizontal displacements by the use of adhesives or by mechanical means.

Under sections 12 and 25 of the 11th edition (1973) of the AASHTO specification (19), entitled "Elastomeric Bearings", a number of changes were made. Both plain (consisting of elastomer only) and laminated bearings of rectangular or circular shapes were introduced. Laminated pads were limited to hardnesses not greater than 70 durometer whereas plain pads were restricted to conditions where little movement was anticipated. To take care of stability requirements, the following pad criteria had to be met:

Plain:	minimum	$L = 5T$, $W = 5T$, $D = 10T$.
Laminated:	minimum	$L = 3T$, $W = 2T$, $D = 6T$.

where,

L = gross length of rectangular bearing parallel to longitudinal axis of the bridge,
W = gross width of bearing perpendicular to the longitudinal axis of the bridge,
D = gross diameter of a circular bearing,
T = total thickness of the elastomer present in a bearing.

Table 2.1 Physical Properties of Neoprene 1961 AASHTO (17)

Grade (Durometer)	60	70
Original Physical Properties		
Hardness ASTM D 676 Tensile strength, ASTM D-412, minimum psi (MPa) Elongation at break, minimum percent	60 ±5 2500 (17.24) 350	70 ±5 2500 (17.24) 300
Accelerated tests to Determine Long Term Aging Characteristics		
Oven Aged - 70 Hrs./212F (100C), ASTM D-573		
Hardness, points change, maximum Tensile Strength. % change, maximum Elongation at break, % change maximum	0 to +15 ±15 -40	0 to +15 ±15 -40
*Ozone - 100 pphm in Air by Volume - 20% Strain - 100+2F. (38 + 1*C)		
ASTM D-1149 100 hours	No cracks	No cracks
Compression Set - 22 Hrs./158F (70C), ASTM D-395 - Method B		
% Maximum	25	25
Low Temperature Stiffness - ASTM D-797		
At 40F. (5C), Young's Modulus, maximum psi (MPa)	10,000 (69)	10,000 (69)
Tear Test - ASTM D-624 - Die "C"		
Pounds/lin. in, minimum (kg/mm)	250 (4.5)	225 (4)

The bearing had to be secured against horizontal displacement only when the dead and live load uplift forces reduced the average pressure to less than 200psi (1.38MPa). Furthermore, compressive strains in the bearing were limited to 7 percent (previous specifications (17, 18) allowed compressive strains up to 15 percent). Plots obtained from rubber manufacturers which were used to obtain compressive deflections showed the relationships of shape factor, stress, and durometer hardness of the elastomer.

The type of elastomer used had to be either 100 percent virgin natural rubber or 100 percent virgin Neoprene with physical properties as in Tables 2.2 and 2.3 (previous specifications (17, 18) permitted Neoprene bearings only). A 10 % variation in these physical properties was allowed when test specimens were cut from the finished product. All the steel used in laminated bearings had to be rolled mild steel (ASTM A36) and the components of the bearing had to be covered by 1/8" of elastomer.

Table 2.2 Physical Properties of Natural Rubber 1973 AASHTO (19)

ASTM Test	Physical Properties	50 Duro	60 Duro	70 Duro
D2240	Hardness	50±5	60±5	70±5
D412	Tensile strength, min. psi (MPa) Ultimate elongation, min %	2500 (17.24) 450	2500 (17.24) 400	2500 (17.24) 300
Heat Resistance				
	Change in durometer hardness, max.	+10	+10	+10
D573 70 hr.@ 158F (70C)	Change in tensile strength, max. % Change in ultimate elongation	-25 -25	-25 -25	-25 -25
Compression Set				
D395 Method B	22 hours @ 158F (70C), max %	25	25	25
Ozone				
D1149	25 pphm ozone in air by volume, 20% strain 100 ± 2F (38± 1C),48 hours mounting procedure D518, procedure A	No cracks	No cracks	No cracks
Adhesion				
D429, B	Bond made during vulcanization, lbs per inch (kg/m)	40 (714)	40 (714)	40 (714)
Low Temperature Test				
D746 Procedure B	Brittleness at -40F (-40C)	No failure	No failure	No failure

Table 2.3 Physical Properties of Neoprene 1973 AASHTO (19)

ASTM Test	Physical Properties	50 Duro	60 Duro	70 Duro

D2240	Hardness	50±5	60±5	70±5
D412	Tensile strength, min. psi (MPa) Ultimate elongation, min %	2500 (17.24) 400	2500 (17.24) 350	2500 (17.24) 300
Heat Resistance				
	Change in durometer hardness, max points	+15	+15	+15
D573 70 hr. @ **158F (70C)**	Change in tensile strength, max. % Change in ultimate elongation	-15 -40	-15 -40	-15 -40
Compression Set				
D395 Method B	22 hours @ 158F (70C), max %	35	**35**	**35**
Ozone				
D1149	100 pphm ozone in air by volume, 20% strain 100 ± 2F (38± 1C),48 hours mounting procedure D518, Procedure A	No Cracks	No Cracks	No Cracks
Adhesion				
D429, B	Bond made during vulcanization, lbs per inch (kg/m)	40 (714)	40 (714)	40 (714)
Low Temperature Test				
D746 Procedure B	Brittleness at -40F (-40C)	No Failure	No Failure	No Failure

______ indicates changes made to Table 2.1 from 1961 AASHTO specification

For quality assurance, the mechanical properties of the finished bearings were verified by laboratory tests. One test limited the compressive strain to a maximum of 7 percent at 800psi (5.52MPa) average unit pressure or at the design dead and live load. Another test limited the shear resistance of the bearing at 25% shear strain after an extended 4-day ambient temperature of -20^{o}F (-7^{o}C) to the values given is Table 2.4.

Table 2.4 Shear Resistance Values for NR and Neoprene 1973 AASHTO (19)

Shear Resistance	Elastomer Type	Durometer
30psi (0.207MPa)	Natural Rubber	50
40psi (0.276MPa)	Natural Rubber	60
50psi (0.345MPa)	Natural Rubber	70
50psi (0.345MPa)	Neoprene	50
75psi (0.517MPa)	Neoprene	60
110psi (0.759MPa)	Neoprene	70

In both the 12th edition (1977) of the AASHTO specifications (20) and the 13th edition (1983) of the AASHTO specifications (21) two changes were made. Dimension tolerances for bearings were introduced (see Table 2.5) and the previous stability requirements (19) for bearings were changed to the following:

Plain: minimum $L = 5T$,
$W = 5T$,
$D = 6T$. ($D = 10T$ in the previous specification)

Laminated: minimum $L = 3T$,
$W = 2T$,
$D = 4T$. ($D = 6T$ in the previous specification)

In sections 14 and 25 of the 14th edition (1989) of the AASHTO specification (22), entitled "Elastomeric Bearings", a number of changes were made. For the first time, the use of tapered pads was discouraged. The thickness of any external steel plate was limited to at least the thickness of the elastomer layer to which the steel plate was bonded to. The specification also encouraged the use of the shear modulus and creep deflection properties of the elastomer (if known) in design. If such properties were not specified, values given in Table 2.6 had to be used instead. When the shear modulus values from Table 2.6 were used in design, the low range had to used for compressive strength calculations and the high range for shear stress calculations.

Table 2.5 Dimension Tolerances for Elastomeric Bearings 1977 and 1983 AASHTO (20, 21)

(1) Overall Vertical Dimensions Average Total Thickness 1 1/4" (31.8mm) or less Average Total Thickness over 1 1/4" (31.8mm)	 -0, +1/8in. (3mm) -0, +1/4in. (6mm)
(2) Overall Horizontal Dimension 36in. (914mm) and less over 36in. (914mm)	 -0, +1/4in. (6mm) -0, +1/2in. (6mm) 12th edition -0, +1/4in. (6mm) 13th edition
(3) Thickness of Individual Layers of Elastomer (Laminated Bearing)	 ±1/8in. (3mm)
(4) Variation from a Plane Parallel to the Theoretical Surface (as determined by measurements at Top Sides Individual Nonelastic Laminates	 1/8in. (3mm) 1/4in. (6mm) 1/8in. (3mm)
(5) Position of Exposed Connection Members	1/8in. (3mm)
(6) Edge Cover of Embedded Laminates or Connection Members	 -0, +1/8in. (3mm)
(7) Size of Holes, Slots, or Inserts	±1/8in. (3mm)
(8) Position of Holes, Slots, or Inserts	±1/8in. (3mm)

Table 2.6 Shear Modulus and Creep Properties of Elastomers 1989 AASHTO (22)

Hardness (Shore"A")	50	60	70
Shear Modulus at 73F (23C) psi (MPa)	85-110 (0.60-0.77)	120-155 (0.85-1.10)	160-260 (1.10-1.79)
creep deflection instantaneous deflection at 25 years	25%	35%	45%

Laminated pads were limited to hardnesses not greater than 60 durometer (previous specifications (19, 20, 21) allowed 70 durometer), whereas plain pads up to 70 durometer were permitted because of their satisfactory use in the past. The compressive stresses given in the previous AASHTO specifications (17, 18, 19, 20, 21) were changed to meet the following requirements:

$\sigma_c \leq GS/\beta$, where G = shear modulus
S = Shape Factor
β = 1.0 for internal layers of reinforcement
= 1.4 for cover layers
= 1.8 for plain pads

nor shall it exceed

$\sigma_c \leq$ 1,000 psi (6.90 MPa) for steel laminated pads
$\sigma_c \leq$ 800 psi (5.52 MPa) for plain pads

In cases where horizontal shear translation is prevented, the allowable compressive stress (σ_c) could be increased by 10%. All values for compressive strains had to obtained from Figure 2.16 for 50 and 60 durometer materials, respectively. No curve was given for a 70 durometer material even though it was still permitted for plain bearing pads. The effects of creep had to be added to the instantaneous deflections when considering long term deflections.

Figure 2.16 Compressive Stress-Strain Curves for 50 and 60 Durometer Elastomers (22)

A new requirement on the rotation between the top and bottom surfaces of the bearing was introduced in this edition of the AASHTO specification. Such rotations were limited to the following:

$L\alpha_L + W\alpha_W \leq 2\Delta_c$ for rectangular pads

$D(\alpha_L^2 + \alpha_W^2)^{1/2} \leq 2\Delta_c$ for circular pad

where, α_L = relative rotation of top and bottom surfaces of bearing about an axis perpendicular to the longitudinal axis (radian).

α_W = relative rotation of top and bottom surfaces of bearing about an axis parallel to the longitudinal axis (radian).

Δ_c = instantaneous compressive deflection of bearing.

The stability requirements for bearings were changed to the following:

<u>Plain:</u> minimum L = 5T,
W = 5T,
D = 6T.

<u>Laminated</u>: minimum L = 3T,
W = 3T, (W = 2T in the previous specification)
D = 4T.

In addition, the use of holes in laminated bearings was discouraged. All pads had to be anchored (secured against horizontal movement) when the compressive forces exceeded the horizontal forces by 4 times. If the bearing was attached to both its top and bottom surfaces, the attachment had to be such that no tension was allowed in the vertical direction. The dimensional tolerances for both plain and reinforced bearings were changed and the new values are given in Table 2.7.

Bearing tests and acceptance criteria were broken down into 2 levels. Level I required the manufacturer to load each steel reinforced bearing to 1.5 times the maximum design load. If the bulging pattern implied misplacement of laminates or poor laminate bond, and if there existed 3 separate surface cracks which were greater than 0.08in. (2mm) wide and 0.08in. (2mm) deep, the bearing had to be rejected. In addition, tensile strength, elongation at break, durometer hardness, bond strength, and ozone resistance tests had to be performed for each production lot of bearings.

Table 2.7 Dimension Tolerances for Elastomeric Bearings 1989 AASHTO (22)

(1)	Overall Vertical Dimensions Average Total Thickness 1 1/4" (32mm) or less Average Total Thickness over 1 1/4" (32mm)	 -0, +1/8in. (3mm) -0, +1/4in. (6mm)
(2)	Overall Horizontal Dimension 36in. (0.914m) and less over 36in. (0.914m)	 -0, +1/4in. (6mm) **-0, +1/2in. (12mm)**
(3)	Thickness of Individual Layers of Elastomer (Laminated Bearing Only at any point within the bearing	 **±20% of design value but no more than ±1/8in.(±3mm)**
(4)	Variation from a Plane Parallel to the Theoretical Surface (as determined by measurements at the edges of the bearings) Top Sides	 **slope relative to the bottom of no more than 0.005 radian** 1/4in. (6mm)
(5)	Position of Exposed Connection Members	 1/8in. (3mm)
(6)	Edge Cover of Embedded Laminates or Connection Members	 -0, +1/8in. (-0, +3mm)
(7)	Size of Holes, Slots, or Inserts	±1/8in. (3mm)
(8)	Position of Holes, Slots, or Inserts	±1/8in. (3mm)

______ indicates changes made to Table 2.5 from 1977 and 1983 AASHTO specifications

Level II criteria were for more critical situations and had to be performed in addition to all the tests listed under Level I criteria. Level II tests included shear modulus and compressive stiffness tests performed in accordance with ASTM D4014 (23). The shear modulus was to be determined either by testing a piece of the finished bearing as specified in ASTM D4014 (23) or by performing a non-destructive test on the complete bearing. Shear modulus values had to fall within ±15% of the value specified in the design document or within the limits given in Table 2.6. The compressive stiffness tests had to be performed on the complete bearing and all values obtained had to vary by no more than ±10% from the median value of all bearings or ±20% from the design value, if specified.

In sections 14 and 18 of the current 15th edition (1992) of the AASHTO specification (24), entitled "Elastomeric Bearings", an additional number of changes were made. Tapered elastomer layers in reinforced bearings are no longer allowed. The value of shear modulus, G, at 73^{o}F (23^{o}C) shall be used as the basis for design. If the elastomeric material is explicitly specified by shear modulus, that value shall be used in design and other values shall be obtained from Table 2.8. If on the other hand, the material is specified by hardness, the shear modulus shall be taken as the value from the range for that hardness from Table 2.8.

Table 2.8 Elastomer Properties at Different Hardnesses 1992 AASHTO (24)

Hardness (Shore"A")	50	60	70
Shear Modulus at 73F (23C) psi (MPa)	**95-130 (0.68-0.93)**	**130-200 (0.93-1.43)**	**200-300 (1.43-2.14)**
creep deflection instantaneous deflection at 25 years	25%	**45%**	45%

______ indicates changes made to Table 2.6 from 1989 AASHTO specification

Shear modulus values larger than 200psi (1.379 MPa) or hardnesses larger than 60 shall not be used for reinforced bearings. In addition, no bearing can have a hardness value larger than 70 durometer or a shear modulus larger than 300psi (2.069MPa). For bearing design purposes, all bridge sites are classified according to temperature zones A through E. These zones are defined by their extreme low temperatures or the largest number of consecutive days for which the temperature has remained below 32^{o}F (0^{o}C). These values are given in Table 2.9.

For the first time in the AASHTO specification, two design procedures (Method A and Method B) for elastomeric bearings were provided. Method A is simple but gives more conservative designs. Bearings designed according to Method B will be more highly stressed and will require more stringent tests.

Table 2.9 Low Temperature Zones and Elastomer Grades 1992 AASHTO (24)

Low Temperature Zone	**A**	**B**	**C**	**D**	**E**
50 Year Low Temperature, F (C)	0 (0)	-20 (-29)	-30 (-34)	-45 (-43)	All others
Maximum number of consecutive days when the temperature does not rise above 32F (0C)	3	7	14	N/A	N/A
Minimum Low Temperature elastomer grade without special provisions	0	2	3	4	5
Minimum Low Temperature elastomer grade with special provisions	0	0	2	3	5

Method A can be used for the design of steel reinforced, fabric reinforced, or plain bearings. The allowable compressive stresses are given below:

$\sigma_{c\,,\,TL} \leq GS/\beta$, where G = shear modulus
S = Shape Factor
β = 1.0 for internal layers of reinforcement
= 1.4 for cover layers and 1.8 for plain pads

nor shall it exceed

$\sigma_c \leq 1{,}000$ psi (6.90MPa) for steel reinforced pads
$\sigma_c \leq 800$ psi (5.52MPa) for plain or fabric reinforced pads

These stress limits can be increased by 10% in cases where horizontal shear deformations are prevented. For bearings with different layer thicknesses, the value for S used shall be the one that gives the smallest S/β. Compressive stress strain curves shown in Figure 2.17 for 50 and 60 durometer steel reinforced bearings shall be used in the calculations of the compressive deflections. The same curves can be used for plain pads, only if the shape factor values are replaced by S/1.8.

Method B is an optional design procedure for steel reinforced bearings only. For bearings subjected to horizontal deformations, the compressive stresses shall be as follows:

$\sigma_{c,\,TL} \leq 1{,}600$ psi (11.0 MPa)

$\sigma_{c\,,\,TL} \leq 1.66GS/\beta$

$\sigma_{c\,,\,LL} \leq 0.66GS/\beta$

When bearings are not subjected to horizontal deformations, the compressive stresses shall be as follows:

$\sigma_{c,\,TL} \leq 1{,}600$ psi (11.0 MPa)

$\sigma_{c\,,\,TL} \leq 2.00GS/\beta$

$\sigma_{c\,,\,LL} \leq 1.00GS/\beta$ where, $\beta = 1.0$ for internal layers and 1.4 for cover layers

Figure 2.17 Compressive Stress-Strain Curves for 50 and 60 Durometer Elastomers (24)

The rotation requirements are the same as the ones given in Method A. Bearings that are subjected to combined compression and rotation, the following limits shall be met:

for bearings subject to shear deformations

or

for bearings fixed against shear deformations where, h_{rt} = total elastomer thickness in a bearing.

To satisfy stability requirements, the average compressive stress due to total dead and live load on rectangular bearings shall meet the following limits:

if the bridge is free to translate horizontally

or

if the bridge is not free to translate horizontally

For circular bearings with diameter d, W and L shall be replaced with 0.8d.

The minimum thickness of the steel reinforcement for good quality fabrication should be at least 1/16in. (1.5mm). The elastomer used, be it natural rubber or Neoprene has to meet the quality control test given in Tables 2.10 and 2.11. The dimension tolerances for both plain and reinforced pads were changed to the values shown in Table 2.12. In addition to the short duration compression test listed under level I criteria in the previous AASHTO specification (22), a long duration compression test is required. In this test the bearing shall be loaded in compression to 1.5 times its maximum design load for a minimum period of 15 hours. The bearing shall be rejected for the same reasons as the short duration compression test (22). Finally, concerning installation, the bearing shall be placed on surfaces that are plane to within 1/16in. (1.5mm). Any lack of parallelism between the top of the bearing and the underside of the girder that exceeds 0.01 radian shall be corrected by grouting.

Table 2.10 Natural Rubber Quality Control Tests 1992 AASHTO (24)

ASTM Tests	*PHYSICAL PROPERTIES*			
D 2240 D412	Hardness (Shore A Durometer Tensile Strength, Minimum psi (MPa) Ultimate Elongation, minimum %	50 ±5 **2250** **(15.5)** 450	60 ±5 **2250** **(15.5)** 400	70 ±5 **2250** **(15.5)** 300
	HEAT RESISTANCE			
D 573 70 hours at **212°F (100°C)**	Change in Durometer Hardness, Maximum points Change in Tensile Strength, Max. % Change in Ultimate Elonga., Max. %	+10 -25 -25	+10 -25 -25	+10 -25 -25
	COMPRESSION SET			
D 395 Method B OZONE D1149	22 hours @ **212°F (100°C),** Max. % 25 pphm ozone in air by volume, 20% strain 100°F ±2°F (38°C ±1°C) 100hr. mounting procedure D 518, A	25 No Cracks	25 No Cracks	25 No Cracks
	** *LOW TEMPERATURE BRITTLENESS*			
D 746, B	Grades 0 &2 - No test Required Grade 3 Brittleness at -40°F (-40°C) Grade 4 Brittleness at -55°F (-48°C) Grade 5 Brittleness at -70°F (-57°C)	No Failure	No Failure	No Failure
	** *INSTANTANEOUS THERMAL STIFFENING*			
D 1043	Grades 0 & 2 - @ -25°F (-32°C) Grade 3 - @ -40°F (-40°C) Grade 4 - @ -50°F (-46°C) Grade 5 - @ -65°F (54°C)	Stiffness at test temperature shall not exceed 4 times the stiffness measured at 73°F (23°C)		
	** *LOW TEMPERATURE CRYSTALLIZATION*			
Quad Shear Test	Grade 0 - No Test Required Grade 2 - 7 days @ 0°F (-18°C) Grade 3 - 14 days @ -15°F (-26°C) Grade 4 - 21 days @ -35°F (-37°C) Grade 5 - 28 days @ -35°F (-37°C)	A ±35% strain cycle shall be used, and a complete cycle of strain shall be applied with a period of 100 seconds. The fist 3/4 cycle of strain shall be disregarded and the stiffness shall be determined by the slope of the force deflection curve for the next 1/2 cycle of loading.		

_____ changes made to Table 2.2   ** additions made to Table 2.2

Table 2.11 Neoprene Quality Control Tests 1992 AASHTO (24)

ASTM Tests	*PHYSICAL PROPERTIES*			
D 2240 D412	Hardness (Shore A Durometer Tensile Strength, Minimum psi (MPa) Ultimate Elongation, minimum %	50 ±5 **2250** **(15.5)** 400	60 ±5 **2250** **(15.5)** 350	70 ±5 **2250** **(15.5)** 300
HEAT RESISTANCE				
D 573 70 hours at **212°F** **(100°C)**	Change in Durometer Hardness, Maximum points Change in Tensile Strength, Max. % Change in Ultimate Elonga., Max. %	+15 -15 -40	+15 -15 -40	+15 -15 -40
	COMPRESSION SET			
D 395 Method B OZONE D1149	22 hours @ **212°F (100°C),** Max. % 100 pphm ozone in air by volume, 20% strain 100°F ±2°F (38°C ±1°C) 100hr. mounting procedure D 518, A	35 No Cracks	35 No Cracks	35 No Cracks
	** *LOW TEMPERATURE BRITTLENESS*			
D 746, B	Grades 0 &2 - No test Required Grade 3 Brittleness at -40°F (-40°C) Grade 4 Brittleness at -55°F (-48°C) Grade 5 Brittleness at -70°F (-57°C)	No Failure	No Failure	No Failure
	** *INSTANTANEOUS THERMAL STIFFENING*			
D 1043	Grades 0 & 2 - @ -25°F (-32°C) Grade 3 - @ -40°F (-40°C) Grade 4 - @ -50°F (-46°C) Grade 5 - @ -65°F (54°C)	Stiffness at test temperature shall not exceed 4 times the stiffness measured at 73°F (23°C)		
	** *LOW TEMPERATURE CRYSTALLIZATION*			
Quad Shear Test	Grade 0 - No Test Required Grade 2 - 7 days @ 0°F (-18°C) Grade 3 - 14 days @ -15°F (-26°C) Grade 4 - 21 days @ -35°F (-37°C) Grade 5 - 28 days @ -35°F (-37°C)	A ±35% strain cycle shall be used, and a complete cycle of strain shall be applied with a period of 100 seconds. The fist 3/4 cycle of strain shall be disregarded and the stiffness shall be determined by the slope of the force deflection curve for the next 1/2 cycle of loading.		

_____ changes made to Table 2.3   ** additions made to Table 2.3

Table 2.12 Dimension Tolerances for Elastomeric Bearings 1992 AASHTO (24)

(1)	Overall Height Design Thickness 1 1/4" (32mm) or less Design Thickness over 1 1/4" (32mm)	 -0, +1/8in. (3mm) -0, +1/4in. (6mm)
(2)	Overall Horizontal Dimension 36in. (0.914m) and less over 36in. (0.914m)	 -0, +1/4in. (6mm) -0, +1/2in. (12mm)
(3)	Thickness of Individual Layers of Elastomer (Laminated Bearing Only) at any point within the bearing	 ±20% of design value but no more than ±1/8in. (±3mm)
(4)	Parallelism with Opposite Face Top and Bottom Sides	 0.005 radian **0.02 radian**
(5)	Position of Exposed Connection Members Holes, Slots, or Inserts	 ±1/8in. (3mm)
(6)	Edge Cover of Embedded Laminates or Connection Members	 -0, +1/8in. (-0, +3mm)
(7)	Thickness Top and bottom cover layer if required	-0, the smaller of +1/16 (1.5mm) and +20% of the nominal cover layer thickness
(8)	Size Holes, slots, or inserts	 ±1/8in. (3mm)

______ indicates changes made to Table 2.7

2.5 DuPont's Design Procedure for Neoprene Bearings

In 1959, DuPont published a handout on the design of Neoprene bearings (11). Up to this day, some engineers still use this as a reference tool when designing elastomeric bridge bearings. In this section, the author will try to present a summary of the most important design concepts presented in this reference (11).

DuPont limits the compressive stress on the bearing pad to 800psi (5.52MPa), whereas compressive strains up to 15% are permitted. Compression curves like the ones shown in Figure 2.18 that relate stress, strain, shape factor, and hardness values are used as a design aid to limit the compressive strains in bearings to 15%.

Figure 2.18 Compression Curves for 50, 60, and 70 Durometer Hard Neoprene (11)

The maximum horizontal deformation in the bearing is limited to twice the total thickness of the elastomer. Shear modulus values shown in Table 2.13 are used to calculate the horizontal forces induced in the bearing. The shear modulus increases with a drop in temperature and therefore, the values given in Table 12 are increased by 10%, 25%, and 90% when bearings are designed for temperatures of 20^{o}F (-7^{o}C), 0^{o}F (-18^{o}C), and -20^{o}F (-29^{o}C), respectively. To insure bearing stability, the shortest dimension of the elastomeric pad has to be at least five times the thickness of the elastomer. Finally, slippage can be prevented as long as the shear stress does not exceed one-fifth the compressive stress acting on the elastomer/concrete interface.

Table 2.13 Shear Modulus Values for Neoprene (11)

Hardness (Shore"A")	50	60	70
Shear Modulus at 73F (23C), psi (MPa)	110 (0.759)	160 (1.1)	215 (1.484)

CHAPTER 3
MECHANICAL PROPERTIES OF ELASTOMERIC BEARINGS

The purpose of elastomeric bridge bearings is to support the vertical loads from the bridge deck and beams with minimal deflection and at the same time permit horizontal movement with minimal resistance. In other words, the behavior of an elastomeric bearing is mainly governed by the mechanical properties of the elastomer in both compression and shear. Although there is not a direct correlation between the hardness of an elastomer and its behavior in compression and shear, the hardness property is still used because the test for it is quick and simple.

3.1 Hardness

Unlike metal hardness which is measured by irreversible plastic indentation, elastomer hardness is measured by reversible elastic indentation under a steel point. Hardness is measured in degrees, either British Standard, BS, International Rubber Hardness, IRHD, (25) or Durometer Hardness (26) which is most commonly used today. Hardness is measured by an instrument called a durometer. The durometer Shore A hardness scale ranges from 0 (very soft) to 100 (very hard). Generally, elastomeric bearing pads have durometer shore A hardnesses of 50 to 70 degrees and for this range the IRHD and durometer hardness scales are equivalent. For comparison, the durometer shore A hardness of a soft pencil eraser is about 30, a rubber band is about 40, an inner tube is about 50, a tire tread is about 60, a shoe heel is about 70 , and a shoe sole is about 80 (11, 13).

Unfortunately, hardness measurements are variable and they depend to some extent upon the durometer, the operator, the sample size, and the method of measurement, so that readings taken on the same elastomer may vary by ±5 degrees (6). "Despite the attractiveness and apparent simplicity of employing hardness as a means of characterizing different elastomers, hardness is not one of the fundamental properties which directly enter into the design of a bearing" (13). The hardness of an elastomeric bearing can be controlled by adjusting the amount of filler agent that goes into the compounding of the elastomer. The hardness can be increased by increasing the amount of filler agent. As the elastomer becomes harder, it stops behaving as a perfectly elastic material.

3.2 Compressive Stiffness

The compressive stiffness of an elastomeric bearing is a mechanical property that is of utmost importance to a structural bridge engineer. The ideal bearing would be one that has an infinite compressive stiffness such that the compressive deflections become negligible. In reality, the compressive stiffness of an elastomeric bearing is far from infinity and it is up to the structural engineer to select the most appropriate compressive stiffness of a bearing that will accommodate the loads imposed by the bridge structure above. In addition, the bearing should be able to deform in such a way to absorb any surface irregularities as well as accommodate angle mismatches between the beam and abutment surfaces. There are a number of factors that affect the compressive stiffness of a bearing. Therefore, it is important for the design engineer to be familiar with the methods and techniques available that can be used to control the behavior of an elastomeric bearing.

3.2.1 Design Aids and Limitations: When elastomeric bearings were introduced in the AASHTO specification (17), the compressive deflection of a bearing was limited to 15% of the total elastomer thickness. In 1959, E.I. du Pont de Nemours and Company, in its publication entitled "Design of Neoprene Bearing Pads" (11) also limited the compressive deflection to 15% of the total elastomer thickness. It was not until the 11th edition of the AASHTO specification in 1973 (19) that the compressive deflection requirement of elastomeric bearings was lowered from 15% to 7% of the total elastomer thickness and was kept unchanged up to the most recent 15th edition AASHTO specification (24). In 1983, E.I. du Pont de Nemours and Company published a handout entitled "Engineering Properties of Neoprene Bridge Bearings" (8) in which it limited the compressive deflection to 10% of the total elastomer thickness; a 5% decrease from its originally published document in 1959 (11).

Stress-strain compressive curves for different shape factors and durometer hardness were developed experimentally by various researchers (9, 11, 27) to serve as an aid in the design of elastomeric bearings. Since plain elastomeric bearings were introduced before steel laminated bearings, stress-strain compression curves for plain bearings were used for the design of both plain and laminated bearings (11, 19, 20, 21, 22) (see Figures 2.15 and 2.17). Through the years, the use of steel laminated bearings became more popular and therefore similar stress-strain compression curves were introduced for steel laminated bearings (1, 8) (see Figure 2.16). The same curves could be also used for plain bearings by simply dividing the shape factor values by 1.8.

3.2.2 Compression Modulus: In general terms, the compressive stress, σ_c, of an elastomeric bearing can be written in the form:

$$\sigma_c = E_c \varepsilon_c \qquad \text{(Eq. 3.1)}$$

where,

$\sigma_c = F_c/A$

F_c = compressive force

A = cross-sectional area

E_c = compressive modulus

ε_c = compressive strain

The most important parameter in the above equation is the compressive modulus, E_c. A number of researchers have discussed the relationship between E_c and various other factors including Young's modulus, E, and shape of the elastomer (28, 29, 30, 31, 32). Most of the research done in developing these relationships was performed on rubber blocks with lubricated as well as bonded ends. Gent and Meinecke (28) defined E_c of a bonded rubber block as

$$E_c = E f_c \qquad \text{(Eq. 3.2)}$$

where,

E = Young's modulus,

$f_c = f_{c1} + f_{c2}$ and obtained from Table 3.1

$$f_{c1} = 4/3 - (2/3)(ab+h^2)/(a^2+b^2+2h^2) \qquad \text{(Eq. 3.3)}$$

Table 3.1 Compressive Stiffness Factors for Various Cross-Sections (28)

Cross-Section	$\mathbf{f_{c1}}$	$\mathbf{f_{c2}}$
Circle, radius r	1	$r^2/2h^2$
Square, side 2a	1	$0.141\,(2a)^2/h^2$
Rectangle, sides 2a & 2b	equation 3.3	$(2a)^2 q_1 / 3h^2$

h = height of the rubber block; q_1 obtained from Figure 3.1

Lindley (31) described the compression modulus E_c of rubber blocks of circular and square cross-sections which are prevented from slipping at the loading surfaces as:

$$E_c = E(1+2kS^2) \qquad \text{(Eq. 3.4)}$$

where *k* is an empirically determined factor less than one that decreases with an increase in hardness (see Figure 3.2) and *S* is a shape factor defined as the ratio of the cross-sectional area to the force free area.

Figure 3.1 Compression Stiffness Factor q_1 for Rectangular Cross-Section (28)

Figure 3.2 Material Constant k as a Function of Hardness (31)

In Equations 3.2 and 3.4, E is taken to be equal to 3 times the G. This relationship comes from the assumption that rubber obeys the classical theory of elasticity at very low strains (i.e. $E=2G(1+\nu)$) and with a Poisson's ratio very close to 0.5 (0.49989 to be precise (33)). At this point, the author would like to draw the reader's attention to the fact that this ratio (E=3G) is only valid when the rubber is highly elastic (i.e. minimal amounts of filler are present). For harder elastomers, this ratio will no longer apply as it will be shown later in section 3.4.

3.2.3 Factors that Affect Compressive Stiffness: The compressive stiffness of an elastomeric bearing can be increased by raising the shape factor (see Figure 3.3 and Figure 3.4). The shape factor of an elastomeric bearing can be increased by reducing the total elastomer thickness that is free to bulge and/or by increasing the cross-sectional area. Furthermore, inserting steel plates at specific intervals within the bearing will drastically increase the shape factor which in turn will reduce the amount of bulging around the perimeter. In addition, the compressive stiffness can be increased by using a harder elastomer (see Figure 3.4).

Figure 3.3 Compressive Stress-Strain Curves as a Function of Shape Factor S (3)

Figure 3.4 Variation of Compressive Modulus E_c with S and Hardness (7)

3.3 Shear Stiffness

When a bridge beam expands or contracts horizontally, it deforms the elastomeric bearing in shear. The elastomeric bearing in turn resists this deformation by producing shear stresses at the interface of the bearing and the beam as well as at the interface of the bearing and the bridge abutment. These shear stresses have to be controlled so they do not exceed the forces of friction, otherwise, the bearing will start to slip. Therefore, it is important to understand the stress-strain behavior of elastomers in shear in order to produce satisfactory elastomeric bridge bearings.

3.3.1 Stress-Strain Behavior in Shear: Elastomers have a linear stress-strain relationship up to strains of 100%. Even though such strains are possible without causing any rubber deterioration, it is a widely accepted design practice to limit the shear strain of elastomeric bearings to 50% of the total elastomer thickness (1, 8, 11). The stress-strain relationship of an elastomeric bearing is given in the form:

$$\tau = G\gamma \qquad \text{(Eq. 3.5)}$$

where,

τ = shear stress = F_s/A

F_s = shear force

A = cross-sectional area

G = shear modulus

γ = shear strain = Δ/T

Δ = maximum lateral displacement of pad

T = total elastomer thickness

Equation 3.5 is valid for both plain and steel reinforced bearings. The behavior of an elastomeric bearing in shear is independent of the fact that it is reinforced or not since the effective rubber thickness, ERT, is the only part of the bearing that is being sheared. For example, two bearings, one reinforced and another plain, both having the same cross-sectional area, ERT, and base rubber material will behave identically in shear. The reinforced bearing, nevertheless, will be stiffer in compression. The only parameter in eq. 3.5 that affects the behavior of an elastomeric bearing pad in shear is the material property: "shear modulus".

3.3.2 Shear Modulus: Shear modulus is an important engineering property that directly enters into the design of elastomeric bearings. The value of shear modulus is a function of the amount of filler that is present in an elastomeric compound. The rubber technologist can control the amount of filler that is used in the mixing process to come up with shear modulus values that will meet the design requirements of the bridge engineer within 10-15% variation. "Because many laboratories are not setup to measure shear modulus, bearing manufacturers generally use hardness as an indicator of stiffness" (8). Two elastomers of the same hardness obtained from two different rubber manufacturers will not have the same shear modulus values because of the difference in their chemical formulations. Furthermore, hardness measurements can vary by as much as 5 degrees from one operator to another and this translates to an additional 15-20% variation in the actual shear stiffness of a bearing. Therefore, it is not a good engineering approach to replace the shear modulus test with the hardness test.

Considerable amount of research has been done to investigate the effect of compressive stress on the shear modulus of an elastomeric bearing (8, 34). Results from the experimental research showed little change in shear modulus with an increase in the compressive stress at a given shear strain. While the shape factor of an elastomeric bearing has no effect whatsoever on the shear modulus, temperature on the other hand has a lot to do with shear modulus. Figure 3.5 shows the increase of shear modulus with the decrease in temperature. This means that when the temperature drops, the shear stiffness of a bearing as well as the shear stresses induced in it will go up.

<u>3.3.2.1</u> <u>Determination of Shear Modulus:</u> Shear is certainly a more important mode of deformation for engineering applications than tension, nevertheless, tension remains the most common mode for laboratory stress-strain tests (9). The purpose of conducting shear stress-strain tests is to determine the shear modulus of the elastomer. Shear tests are performed on both full

scale elastomeric bearings and small rubber samples cut from elastomeric bearings. In the full scale test, two bearings are sandwiched between three concrete slabs (see Figure 3.6a).

Figure 3.5 Relationship of G to Hardness of Neoprene at Various Temperatures (8)

A compressive force representing the vertical reaction on a bridge beam is applied on the top and bottom concrete slabs. A horizontal shear force is applied on the middle concrete slab to simulate the shear stresses in the elastomeric bearing caused by the expansion and contraction of the bridge beam due to temperature changes. With the compressive load held constant, the middle slab is loaded horizontally until shear strains up to 100% are obtained in both directions. This loading-unloading cycle is repeated several times until the stress-strain curve stabilizes. The linear portion of the final stress-strain curve is used to calculate the shear modulus of the bearing. For example, Lee (35) uses the stress-strain curve between tan15^{o} (0.268) and tan 30^{o} (0.577) in the calculation of the shear modulus (see Figure 3.6b).

Shear modulus tests are also performed on small rubber samples that are obtained from the original elastomeric bearing material. Annex A of the ASTM D4014 specification (23) describes the test procedure and setup that is used to measure the shear modulus. The test setup consists of a quadruple shear test piece made up of four rubber blocks that are bonded to thick rigid steel plates (see

Figure 3.7a). The rubber blocks should have lengths and widths that are at least four times the thickness. The test piece is strained in a tension machine at least 6 times up to an extension equal to the average rubber thickness of one block. The load-displacement curve on the 6th loading cycle is used to measure the shear modulus (see Figure 3.7b).

Figure 3.6 (a) Arrangement of Bearings and Concrete Slabs (b) Loading-Unloading Curves

Figure 3.7 (a) Quadruple Shear Test Piece (b) 1st and 6th Load-Deflection Curves

3.4 Relation between Hardness and other Mechanical Properties

Reference 3 discusses the relationship between hardness, Young's modulus, E, and shear modulus, G. Even though the design of an elastomeric bearing has to do with the knowledge of the elastic modulus of the elastomer, it is a common practice to describe rubber by its indentation hardness - a measure of an indentation produced under a known loading condition. Table 3.2 shows the scatter of published G and E values with respect to durometer hardness of an elastomer. According to Gent, a precise relationship although of somewhat complicated form exists between hardness and E (see Figure 3.8). The relationship between G and E at various hardnesses is also shown in Figure 3.8. For soft highly elastic rubbers (i.e. elastomers with minimal amounts of fillers), E = 3G. As for the case of stiffer materials which show "imperfect elastic behavior" (3), values of E=4G or more are possible. The design engineer should be familiar these relationships, before blindly replacing E with 3G.

Table 3.2 Scatter of Published G and E values with respect to Hardness

	Mechanical Properties E and G Obtained from the Following References								
	Ref. 6	Ref. 12	Ref. 7	Ref. 3	Ref. 22	Ref. 24	Ref. 35	Ref. 10	Ref 11
Hardness (Degrees)	**SHEAR MODULUS G (psi)**								
50	87	93	93	90-115	85-110	95-130	71	91	110
60	145	154	154	135-165	120-155	130-200	114	129	160
70	203	254	251	200-260	160-260	200-300	157	177	215
Hardness (Degrees)	**YOUNG'S MODULUS E (psi)**								
50	334	319	319	320-400	-	-	-	-	-
60	537	645	645	500-600	-	-	-	-	-
70	900	1088	1066	780-900	-	-	-	-	-

Note: 145psi = 1MPa

Figure 3.8 Relations Between Young's Modulus E, Shear Modulus G, and Hardness (3)

CHAPTER 4

STATIC MATERIAL TESTS ON NATURAL RUBBER (NR) BLOCKS

In this chapter, the static material tests conducted on the NR specimens will be discussed. Such material tests include compression, tension, shear, and combined compression and shear. In addition, specimen preparation, test method used, load and displacement measurements, and testing procedures, among others, will be fully explained.

Material properties such as compressive modulus, tensile modulus, and shear modulus for NR specimens measuring 4 x 4 x 1, in. (101.6 x 101.6 x 25.4, mm) and 2 x 2 x 0.5, in. (50.8 x 50.8 x 12.7, mm) will be calculated. The purpose of these tests is to see how well these mechanical properties compare with the ones obtained from the full size NR elastomeric bearings.

4.1 Test Setups

The details of the compression, tension, shear, and combined compression and shear test setups are shown in Figures 4.1 through 4.4. All Steel components including steel plates, welds and bolted connections used in all test setups were designed according to the LRFD specification. The aluminum plates used in the combined compression and shear test setup were designed to resist the bending moment caused by the force in the calibrated bolt.

4.2 Supplier and Ordering Information

Applied Rubber Technology Inc., in Conroe, Texas, supplied the elastomeric bearing pads that were used in this research. Pads measuring 9 x 28 x 1, in. (228.9 x 711.2 x 25.4, mm) were ordered in both nominal shear moduli, G_n, of 100psi (0.69MPa) and 200psi (1.379MPa) instead of specifying the commonly used property of durometer hardness. In addition, a microcrystalline type of wax replaced the commonly used paraffinic wax. No information concerning test requirements or methods of measuring the shear moduli values supplied were provided. Instead it was left to the rubber manufacturer to choose whatever test method or technique was deemed necessary to come up with the requested shear moduli. All other ingredients such as carbon black, and curing agents that go into the chemical composition of the NR were left up to the rubber manufacturer.

4.3 Size of NR Specimens and Method of Cutting

Rubber blocks, 4 x 4 x 1, in. (101.6 x 101.6 x 25.4, mm) and 2 x 2 x 0.5, in. (50.8 x 50.8 x 12.7, mm), were cut from the originally supplied 9 x 28 x 1, in. (228.9 x 711.2 x 25.4, mm) NR bearing pads. The 4 x 4 x 1, in. (101.6 x 101.6 x 25.4, mm) specimens were cut on a rotating steel band saw equipped with a liquid coolant. The rough edges of the blocks were finished smooth with a hand held rotating sander. The finishing operation was carefully done to avoid overheating of the NR blocks. The 2 x 2 x 0.5, in. (50.8 x 50.8 x 12.7, mm) specimens were obtained by first cutting NR blocks into 2 x 2 x 1, in. (50.8 x 50.8 x 25.4, mm) using the same procedure defined above. A rotating jig-saw blade was then used to cut the blocks into thicknesses of 0.5in. (12.7mm).

4.4 Specimen Preparation

Twenty-eight specimens were cut from each of the 100psi (0.69MPa) and 200psi (1.370MPa) NR pads for a total of 56 specimens (Figure 4.5). Half of the twenty-eight specimens measured 4 x 4 x 1, in. (101.6 x 101.6 x 25.4, mm) and the other half measured 2 x 2 x 0.5, in. (50.8 x 50.8 x 12.7, mm). The specimens were numbered in such a way to indicate the type of material, dimension, type of test, and quantity of specimens that fell under the same category (Figure 4.5). The first character stands for the type of material: "1" for G_n of 100psi (0.69MPa), and "2" for G_n of 200psi (1.379MPa). The second character represents the type of test: "C" for Compression, "T" for Tension, and "S" for Shear. The last character simply signifies the number of specimens that fell under the same category of the first three characters. A grid was marked on one side of the specimen to aid in the observation of the behavior of the NR block under various stress concentrations. All markings were done by a silver felt pen.

4.5 Measurement of Specimen Properties

Prior to gluing the natural rubber blocks to the steel surfaces of the steel fixtures, the length, width, thickness, and hardness of each specimen were determined (see Tables 4.1a, 4.1b, 4.1c). The length, width, and thickness of each specimen were measured to the nearest 0.001in. (0.0254mm) by means of a Vernier caliber. The 4in. (101.6mm) and 2in. (50.8mm) specimens deviated from their nominal length or width by as much as 0.140in. (3.6mm) and 0.057in. (1.5mm), respectively. The 1in. (25.4mm) and 0.5in. (12.7mm) specimens deviated from their nominal thickness by as much as 0.130in. (3.3mm) and 0.095in. (2.4mm), respectively.

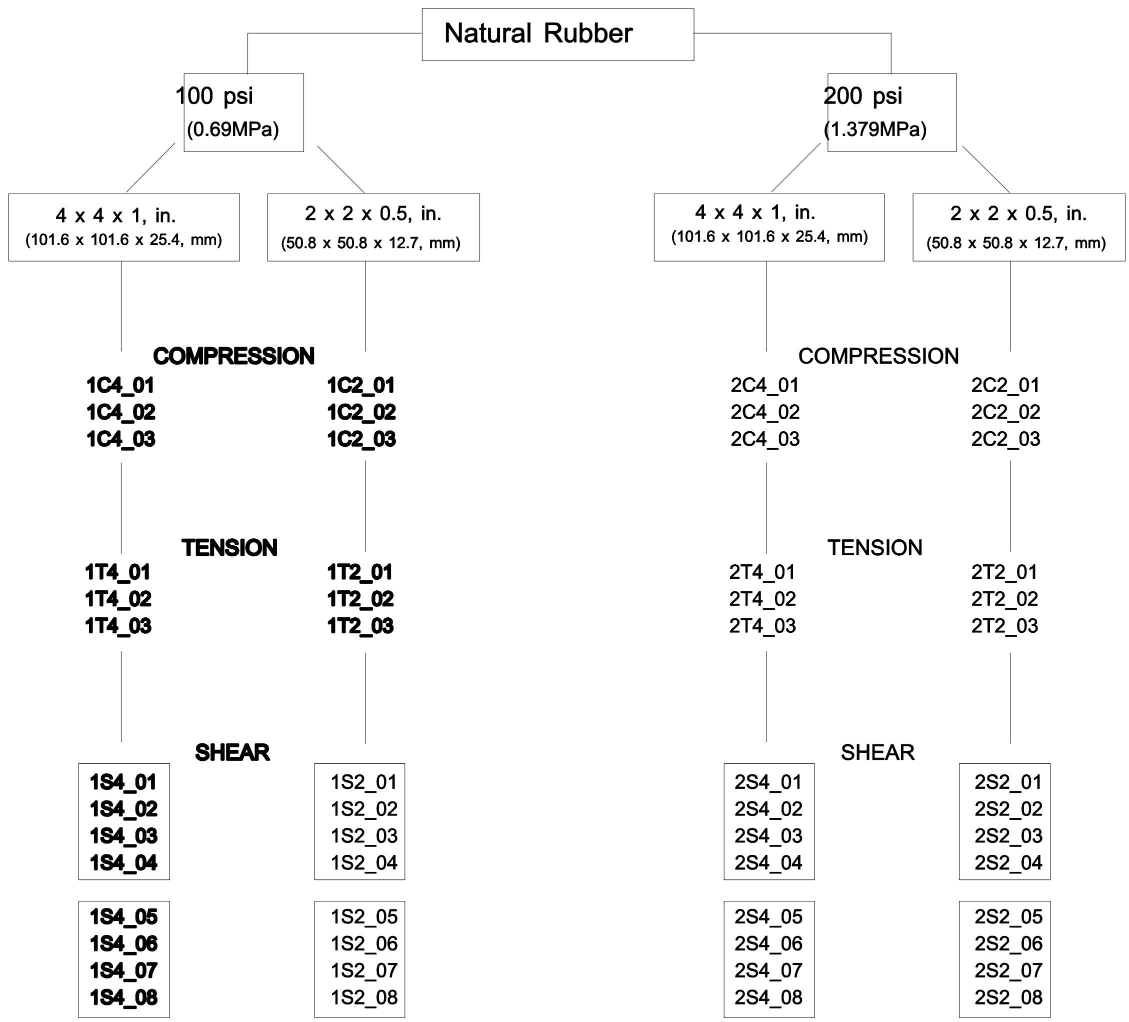

Figure 4.5 Breakdown of the NR Specimens Used in the Test Program

Hardness values were determined by means of a Shore "A" Durometer (ASTM D2240 (26)). The specimen was placed on a hard, horizontal surface and the durometer was held vertically with the point of the indentor at least 0.5in. (12.7mm) from any edge. The presser foot of the durometer was applied to the specimen without shock, keeping the foot parallel to the surface of the specimen. The durometer was held for 1 to 2 seconds and the maximum reading recorded. The durometer hardness measurements varied by as much as 4 units for the specimens with a nominal shear modulus (G_n) of 100psi (0.69MPa) and 200psi (1.379MPa).

4.6 Safety Precautions

In order to avoid any harmful side effects from over exposure to the chemical solvents and adhesives, the cleaning operations were carried out in strict compliance with the Material Safety Data Sheets, MSDS, supplied by the chemical manufacturer. Rubber gloves were worn for skin protection, eye goggles with side shields were utilized to guard the eyes from any splashing chemical liquid, and a respiratory half mask with chemical/organic filter was used for respiratory protection.

4.7 Rubber and Steel Surface Preparation

Certain steps were taken to assure that a good bond between the NR and the steel surfaces was obtained. Both surfaces were properly treated and conditioned to provide an acceptable bonding surface. The steel surface preparation consisted of vapor degreasing, grit blasting, and vapor degreasing. The vapor degreaser used was "Trichloroethylene, C_2HCl_3" and it was brushed onto the steel surface using Q-tips. The purpose of the first vapor degreasing operation was to remove soils such as grease and oil. Blasting consisted of impinging abrasive particles against the surface of the metal with an air stream. The abrasive particles used were "N^{o}5 sand". The second vapor degreasing step was a safety factor designed to remove any abrasive dust or contaminants that may have been present in the blasting material.

The NR surface was treated with a special solvent-based surface conditioner under the brand name "Chemlock 7701." The solvent was carefully applied throughout the pad surface especially on the corners and edges. "Chemlock 7701" altered the surface to make it more compatible with the rubber to steel adhesive. After the solvent flashed off in five minutes or less, the treatment was complete. In order to obtain best adhesion results, bonding the steel to the elastomer was done as soon as the solvent had splashed off.

4.8 Adhesives

A special type of elastomer to metal epoxy under the brand names "Fusor 320" (resin) and "Fusor 310B Black" (hardener) was used for all gluing operations. Fusor 320 was mixed with Fusor 310B Black by the ratio of 2:1 by volume. Both the resin and hardener were thoroughly mixed together. Since the curing time for the epoxy was around 8 hours, all glued surfaces were allowed to dry at least overnight.

The steps used to glue the two surfaces together are listed below:

1. The epoxy was uniformly applied on one surface of the elastomer.
2. The elastomer was then pressed on the treated steel surface with the help of C-clamps until the extra epoxy was squeezed out of the edges of the elastomer.
3. The excess epoxy was wiped off the edges using the round edge of the Q-tip.
4. The glued surface was allowed to dry overnight.
5. The following day, the other side of the elastomer was glued to its corresponding steel surface by following steps 1-4 listed above.

Figure 4.6 shows the gluing stages for the tension and compression specimens, while Figure 4.7 shows the gluing stages for the shear specimens.

4.9 Displacement and Load Measurements

All deformations in the NR blocks due to compression, tension , or shear were measured electronically to the nearest 0.001in. (0.0254mm) by a 2in. (50.8mm) linear potentiometer. A digital displacement gage was used to visually monitor the amount of deformation. A Tinius Olsen universal tension/compression machine was used to measure all the loads in the NR blocks due to compression, tension, and shear. The machine was calibrated prior to testing. In the combined compression and shear test, the compression load was applied by a calibrated bolt. A strain indicator was utilized to measure the amount of strain in the bolt. A load/strain relationship obtained from the calibration of the bolts was used to relate the strain in the bolt to actual compressive loads. A data acquisition system was used to collect and save load and displacement data electronically every 4 seconds.

4.10 Testing Procedures

All the tests were performed at room temperature. Since all the specimens were stored at the test temperature, no special conditioning time was required before loading. The stress-strain relationship in all the tests was based on the initial (undeformed) areas and thicknesses of the NR specimens.

4.10.1 Compression Tests: The compression tests were broken down into two parts. In part I, values of compressive modulus, E_c, were calculated at very small strains (between 4% and 8%), whereas, in part II, the effects of stress relaxation and creep (strain relaxation) were studied at various strains.

In part I of the compression tests, each specimen was loaded up to approximately 12% compressive strain and then unloaded at the same rate (0.02 in./minute, 0.5mm/minute). This loading-unloading cycle was repeated five times in order to "condition" the specimen. The compression modulus was measured on the 5th loading cycle between 4% and 8% strain.

In part II of the compression tests, the 1in. (25.4mm) thick specimens were loaded at a rate of 0.02in/minute, (0.5mm/minute) up to strains corresponding to 1500psi (10.24MPa) and 7500psi (51.7MPa) compressive stresses, while the 0.5in. (12.7mm) thick specimens were loaded at the same rate up to strains corresponding to 1100psi (7.59MPa) and 6000psi (41.38MPa) compressive stresses. The loading was then stopped and the compressive deformation in the specimen was held constant. The specimen was allowed to stress relax for 5 minutes. At the end of the 5 minutes, the machine was turned on and the specimen was unloaded at the same rate. The amount of creep was measured as a percentage of the maximum strain, while the amount of stress relaxation was measured as a percentage drop in the maximum stress.

4.10.2 Tension Tests: The tension tests were broken down into two parts. In part I, each specimen was loaded in tension up to approximately 12% tensile strain and then unloaded at the same rate (0.02in/min, 0.5mm/min). This loading unloading cycle was performed five times in order to "condition" the specimen. The tensile modulus E_t, was measured on the 5th cycle between 4% and 8% strain. In part II of the tension tests, both the 1in. (25.4mm) and 0.5in. (12.7mm) specimens were loaded in tension up to the point of failure at a rate of 0.02in/min, 0.5mm/min). The failure was defined either as a splitting failure in the elastomer itself or as a bond failure at the steel/elastomer interface.

4.10.3 Shear Tests: The shear tests followed the procedure outlined in ASTM D4014 Annex A (23). Six successive loading and unloading cycles up to a deformation equal to the average block thickness were carried out for each shear specimen. The loading and unloading rates were set at 0.3in./min (8mm/min). The 6th loading cycle was used to calculate the shear modulus value.

4.10.4 Combined Compression and Shear Tests: In the combined compression and shear tests, the same specimens tested in simple shear were used. The combined compression and shear tests followed the same testing procedure outlined in ASTM D4014 Annex A (23). Before loading and unloading the specimen 6 successive times to a deformation equal to the average block thickness at a rate of 0.3in./min (8mm/min), a compression force was applied on the specimen through a calibrated bolt. The specimen was sandwiched between two aluminum blocks and a calibrated bolt with two washers and a nut were used to assemble the specimen. The strain gage coming out of the calibrated bolt was wired to the strain indicator, and the nut was turned until the strain recorded by the strain indicator gave the required compressive stress. The combined compression and shear test was performed under two different compressive stresses. The reason for this was to investigate the effect of compressive stress on the calculated shear modulus values. Compressive stresses of approximately 120psi (0.83MPa) and 220psi (1.52MPa) were used for the 0.5in. (12.7mm) thick NR specimens, while compressive stresses of approximately 100psi (0.69MPa) and 150psi (1.03MPa) were used for the 1in. (25.4mm) thick NR specimens.

After the completion of the combined compression and shear tests, the specimens were loaded in simple shear up to the point of failure at a rate of 0.3in./min (8mm/min). The failure was defined either as a splitting failure in the elastomer itself or as a bond failure at the steel/elastomer interface.

CHAPTER 5
ANALYSIS OF RESULTS

5.1 Shear and Combined Compression and Shear Tests

All the shear and combined compression and shear specimens (see Figures 4.3 and 4.4) were tested according to the procedure described in Annex A of ASTM D4014 (23). Six loading and unloading force-displacement cycles were plotted for each test specimen (see Figure 5.1). The force-displacement curves more or less stabilized after the first loading cycle (see Figure 5.1). Since each shear specimen consisted of four NR blocks glued to four steel plates, the stress-strain behavior for one NR block was obtained by using half the load and displacement values from Figure 5.1 and the average area and thickness values from all four NR blocks. Figure 5.2 shows the first and sixth loading stress-strain curves for one NR block. Shear modulus values were calculated from the sixth loading cycle according to the procedure described in Annex A of ASTM D4014 (23). Additional shear modulus values were obtained from the sixth loading cycle between strains of 20% and 40%. The reason for selecting this range was that the stress-strain curve was found to be linear. Both methods used to calculate the shear modulus values are graphically represented in Figure 5.2. Shear modulus values were also obtained for the combined compression and shear tests using the same methods described above. Table 5.1 summarizes the calculated shear modulus values for all the shear and combined compression and shear specimens.

In general, the calculated shear modulus values for the 2 x 2 x 0.5 in. (50.8 x 50.8 x 12.7 mm) specimens were about 10% higher than those for the 4 x 4 x 1in, (101.6 x 101.6 x 25.4 mm) specimens. In addition, the method described in Annex A of ASTM D4014 (23) gave shear modulus values that were about 17% larger than the ones obtained between 20 and 40% strain. Section A1.1 in ASTM D4014 (23) specifically mentions that shear modulus values obtained using this method will be even larger for elastomers with hardnesses greater than 55 durometer. In other words, since 60 and 70 durometer elastomers are used in this research, the ASTM method will overestimate the shear modulus values. In the combined compression and shear tests it was found that the shear modulus values increased slightly with an increase in compressive stress. For example, the shear modulus value for the 1S4_01, 02, 03, 04 specimen increased by 3% and 4% when the compressive stress was raised from zero to 112psi (0.77MPa) and 146psi (1MPa), respectively. This increase is small so that the effect of compressive stress can be neglected.

After the shear modulus values were determined, the shear specimens were loaded to failure. Figure 5.3 shows the complete shear stress-strain curve for one of the four NR blocks from the 1S4_01, 02, 03, 04 specimens. It is obvious from Figure 5.3 that the stress-strain behavior is almost linear up to strains of 100%. Figures 5.4, 5.5, 5.6, and 5.7 show the shear specimen 1S4_01, 02, 03, 04 at 50% strain, 100% strain, 150% strain, and at bond failure, respectively. After loading all the specimens to failure, the strength of the epoxy in shear was found to vary from 200psi (1.38MPa) to 450psi (3.1MPa) for elastomers with nominal shear modulus of 100psi (0.69MPa) and from 350psi (2.4MPa) to 550psi (3.79MPa) for elastomers with nominal shear modulus of 200psi (1.38MPa). By knowing the strength of the epoxy in shear, future specimens can be better designed to resist the forces induced in the NR blocks.

Figure 5.3 Shear Stress-Strain Curve for one NR Block from the 1S4_01, 02, 03, 04 Specimen

5.2 Compression Tests

All the compression specimens (see Figure 4.1) were loaded up to approximately 12% strain and then unloaded back to zero. Five loading and unloading stress-strain cycles were plotted for each test specimen (see Figure 5.8). It was noticed that the compressive stress-strain curves more or less stabilized after the first loading cycle (see Figure 5.8). The compressive modulus, E_c, was calculated from the fifth loading cycle as the slope of the best fit line passing through the collected data points between 4% and 8% compressive strain. Since 7% compressive strain is the maximum permissible value for elastomeric bearings, measuring E_c between 4% and 8% strain seemed appropriate. Furthermore, there is no ASTM test available for measuring the compressive modulus of an elastomer. Figure 5.9 shows the fifth loading cycles of all the 4 x 4 x 1in. (101.6 x 101.6 x 25.4mm) specimens and their average E_c values computed between 4% and 8% strain. Table 5.2 summarizes the calculated compression modulus values for all the compression specimens.

The calculated E_c values of the 2 x 2 x 0.5in. (50.8 x 50.8 x 12.7mm) specimens were higher than the 4 x 4 x 1in. (101.6 x 101.6 x 25.4mm) specimens by 18% and 10% for nominal shear modulus, G_n, values of 100psi (0.69MPa) and 200psi (1.38MPa), respectively. Furthermore, the calculated E_c values of the G_n=200psi (1.38MPa) specimens were higher than the G_n=100psi (0.69MPa) specimens by 50% and 40% for specimen sizes of 4 x 4 x 1in. (101.6 x 101.6 x 25.4mm) and 2 x 2 x 0.5in. (50.8 x 50.8 x 12.7mm), respectively. Compression modulus values were also calculated according to Equation 3.2 (E_c=Ef_c). The value of Young's modulus, E, was taken to be 4G and 4.3G for the 60 durometer (i.e G_n=100psi (0.69MPa)) and 70 durometer (i.e. G_n=200psi (1.38MPa)) specimens, respectively, and obtained from Figure 3.8. The average shear modulus values calculated according to the ASTM 4014 (14) and 20-40% methods were used in Equation 3.2 to obtain compressive modulus values. Table 5.3 compares the measured E_c values with the ones calculated from Equation 3.2. The measured E_c values were found to be higher than the calculated ones from Equation 3.2 by about 30% and 12% when shear modulus values from the ASTM 4014 (23) and 20-40% strain methods were used, respectively.

After determining the compressive modulus values, all the specimens were loaded up to strains of 30-40% and 45-55% in order to study their stress relaxation and creep (strain relaxation) behavior. The stress relaxation was measured as a percentage drop in the maximum stress after the specimen was held at a constant strain for five minutes. Creep, on the other hand, was measured as a percentage of the maximum compressive strain.

Table 5.4 summarizes the creep and stress relaxation values for all the compression specimens. It was noticed that the % creep values increased by as much as 210% and 174% for the 4 x 4 x 1in. (101.6 x 101.6 x 25.4mm) and 2 x 2 x 0.5in. (50.8 x 50.8 x 12.7mm) specimens, respectively, when the maximum compressive strain was raised from about 30% to about 50%. On the other hand, the stress relaxation increased by as much as 22% and 135% for the 4 x 4 x 1in. (101.6 x 101.6 x 25.4mm) and 2 x 2 x 0.5in. (50.8 x 50.8 x 12.7mm) specimens, respectively.

Figure 5.10 shows the compressive stress-strain curve for the 1C4_01 NR block with stress relaxation after five minutes and creep behavior, while Figure 5.11 shows specimen 1C4_02 at 55% compressive strain. From Figure 5.11, it is obvious that the block bulges more at the center, where the stress concentrations are high, than at the ends, where the stress concentrations are low.

Figure 5.10 Compressive Stress-Strain Curve for Specimen 1C4_01 Showing Stress Relaxation and Creep

Figure 5.11 Compressive Specimen 1C4_02 at 55% Strain

5.3 Tension Tests

All the tension specimens (see Figure 4.2) were loaded up to approximately 12% strain and then unloaded back to zero. Five loading and unloading stress-strain cycles were plotted for each test specimen (see Figure 5.12). It is obvious from Figure 5.12 that the tensile stress-strain curve stabilized after the first loading cycle. The tensile modulus, E_t, was determined from the fifth loading cycle as the slope of the best fit line passing through the collected data points between 4% and 8% strain. Figure 5.13 shows the fifth loading cycles of all the 4 x 4 x 1in. (101.6 x 101.6 x 25.4mm) specimens and their average E_t values measured between 4% and 8% strain. Table 5.5 summarizes the tensile modulus values for all the tension specimens.

The E_t values of the 2 x 2 x 0.5in. (50.8 x 50.8 x 12.7mm) specimens were higher than the 4 x 4 x 1in. (101.6 x 101.6 x 25.4mm) specimens by 20% and 1% for nominal shear modulus, G_n, values of 100psi (0.69MPa) and 200psi (1.38MPa), respectively. Furthermore, the calculated E_t values of the G_n=200psi (1.38MPa) specimens were higher than the G_n=100psi (0.69MPa) specimens by 54% and 28% for specimen sizes of 4 x 4 x 1in. (101.6 x 101.6 x 25.4mm) and 2 x 2 x 0.5in. (50.8 x 50.8 x 12.7mm), respectively.

When the tensile modulus values were determined, all the specimens were loaded up to the point where either the rubber or the epoxy failed. After loading all the specimens to failure, the strength of the epoxy in tension was found to vary from 170psi (1.17MPa) to 330psi (2.28MPa) for elastomers with nominal shear modulus of 100psi (0.69MPa) and from 190psi (1.31MPa) to 420psi (2.90MPa) for elastomers with nominal shear modulus of 200psi (1.38MPa). By knowing the strength of the epoxy in tension, future specimens can be better designed to resist the forces induced in the NR blocks.

Figure 5.14 shows the complete tensile stress-strain curve for the 1T4_03 specimen at various loading stages. Figures 5.15 through 5.22 show the actual test specimen at the stages indicated in Figure 5.14. Out of all the tests specimens, 1T4_03 was the only one to show a good failure sequence in the rubber material. When specimen 1T4_03 was at a strain of about 80%, a small hole about the size of a peanut appeared in the middle of the NR block (see Figure 5.18) at the same time that a popping sound was heard. The splitting in the rubber propagated from this initial hole and spread all over the NR block (see Figures 5.18-5.22).

Figure 5.15 Tension Specimen 1T4_03 at 20% Strain

Figure 5.16 Tension Specimen 1T4_03 at 50% Strain

Figure 5.17 Tension Specimen 1T4_03 at 78% Strain

Figure 5.18 Tension Specimen 1T4_03 at Initial Rubber Failure

Figure 5.19 Tension Specimen 1T4_03 at 90% Strain (Tear Propagation)

Figure 5.20 Tension Specimen 1T4_03 at 100% Strain

Figure 5.21 Tension Specimen 1T4_03 at 110% Strain

Figure 5.22 Tension Specimen 1T4_03 at 115% Strain

5.4 Discussion of Test Results

The purpose of the experimental portion of this report is to investigate certain test parameters in order to establish the influence of test technique, specimen size, and material type on the structural properties of an elastomer, and also to determine if there is a consistent relationship between the tensile modulus, E_t, compressive modulus, E_c, and shear modulus, G, values of the tested specimens.

Compression, tension, shear, and combined compression and shear tests were performed on 2 x 2 x 0.5in. (50.8 x 50.8 x 12.7mm) and 4 x 4 x 1in. (101.6 x 101.6 x 25.4mm) natural rubber NR specimens with nominal shear modulus, G_n, values of 100psi (0.69MPa) and 200psi (1.38MPa). The compression and tension specimens (see Figures 4.1 and 4.2) used to measure E_c and E_t, respectively, consisted of one NR block, while the shear and combined compression and shear specimens (see Figures 4.3 and 4.4) used to measure G, consisted of four NR blocks. Since the average stress-strain relationship of four NR blocks was used to measure the shear modulus value, the shear test gives a better representation of the material property of the elastomer. Rubber manufacturers perform a different type of tension test (ASTM D412 (36)) in which a tensile coupon is tested at high tensile strains (i.e. 100% to 300% elongation) and a different type of compression test (ASTM D395 (37)) in which small rubber specimens are compressed under a known load or displacement for a certain period of time at elevated temperatures. Compared to these two ASTM tests (36, 37), the shear modulus test (ASTM D4014 (23)) is the most expensive of all and is usually not performed unless it is requested by the rubber purchaser.

As is was mentioned earlier, the measured shear modulus values of the 2 x 2 x 0.5in. (50.8 x 50.8 x 12.7mm) specimens were about 10% higher than the 4 x 4 x 1in. (101.6 x 101.6 x 25.4mm) specimens. The ASTM D4014 (23) test limits the specimen size to no less than 0.25in. (6mm) thick and to a square or rectangular cross-section with the lengths and widths at least four times the thickness. In order to achieve consistent test results, the specimen size in the ASTM test should be either specified or limited to a certain range of dimensions.

After measuring the material properties of E_c, E_t and G of the elastomers from all the test specimens, their average values were compared to see whether or not any interrelationship exists. Table 5.6 shows the average tensile and compressive modulus values obtained from three specimens, and the average shear modulus values obtained from two specimens. Table 5.6 shows that the measured shear modulus values are 20%-30% higher than the 100psi (0.69MPa) nominal shear modulus material, and 10-20% lower than the 200psi (1.38MPa) nominal shear modulus material.

Furthermore, the ratio of the compressive modulus to the tensile modulus varies from 1.79 to 1.96, the ratio of the compressive modulus to the shear modulus varies from 13.75 to 14.90, and the ratio of the tensile modulus to the shear modulus varies from 7.28 to 8.3. When the E_c to G ratios for the 4 x 4 x 1in. (101.6 x 101.6 x 25.4mm) and 2 x 2 x 0.5in. (50.8 x 50.8 x 12.7mm) specimens were averaged, their values were 14.38 and 14.57 for G_n=100psi (0.69MPa) and G_n=200psi (1.38MPa) rubber material, respectively. When the E_t to G ratios for the 4 x 4 x 1in. (101.6 x 101.6 x 25.4mm) and 2 x 2 x 0.5in. (50.8 x 50.8 x 12.7mm) specimens were averaged, their values were 7.81 and 7.80 for G_n=100psi (0.69MPa) and G_n=200psi (1.38MPa) rubber material, respectively.

The measured shear modulus values of the 4 x 4 x 1in. (101.6 x 101.6 x 25.4mm) specimens with G_n=100psi (0.69MPa) and G_n=200psi (1.38MPa) were 118psi (0.81MPa) and 162psi (1.12MPa), respectively, while the measured shear modulus values of the full scale elastomeric bearings were 113psi (0.78MPa) and 148psi (1.02MPa), respectively. The full scale elastomeric bearing specimens measured 9 x 14 x 2in. (229 x 356 x 51mm) with a total elastomer thickness of 1.75in. (44.5mm) and two 0.125in. (3.2mm) steel plates. In other words, the shear modulus values of the small scale specimens were higher than the shear modulus values of the full scale specimens by 4% and 9% for G_n= 100psi (0.69MPa) and G_n=200psi (1.38MPa) rubber material, respectively.

Finally, the combined compression and shear tests gave shear modulus values that were about 3% higher than the ones obtained from the simple shear test. This increase is small enough that the effect of compressive stress can be neglected.

CHAPTER 6
SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

6.1 Summary

In this study, natural rubber blocks of nominal shear modulus, G_n, values of 100psi (0.69MPa) and 200psi (1.38MPa) and measuring 4 x 4 x 1in. (101.6 x 101.6 x 25.4mm) and 2 x 2 x 0.5in. (50.8 x 50.8 x 12.7mm) were tested in compression, tension, shear, and combined compression and shear. A detailed description of the sample preparation, test setups used and methods of testing are presented in Chapter Four of this report. Stress-strain relationships were obtained from all tests and material properties such as shear modulus, G, compressive modulus, E_c, and tensile modulus, E_t were calculated. All test results obtained from these experiments are fully presented in Chapter Five of this report.

6.2 Conclusions

After performing the experiments, it was noticed that the 2 x 2 x 0.5in. (50.8 x 50.8 x 12.7mm) specimens gave higher material property values of E_c, E_t, and G than the 4 x 4 x 1in. (101.6 x 101.6 x 25.4mm) specimens. Therefore, it is concluded that the specimen size affects the material properties of an elastomer. The shear and combined compression and shear tests were performed according to the procedure outlined in ASTM D4014 Annex A (23). Shear modulus values calculated according to the equation presented in the ASTM D4014 (23) test were higher than the ones calculated from the straight line portion of the sixth loading stress-strain curve between 20% and 40% strain. It is concluded that the shear modulus values computed between 20% and 40% strains for the 4 x 4 x 1in. (101.6 x 101.6 x 25.4mm) specimens better predict the shear modulus values obtained from full scale elastomeric bearings than the 2 x 2 x 0.5in. (50.8 x 50.8 x 12.7mm) specimens. The shear modulus values of the small scale specimens were higher than the shear modulus values of the full scale specimens by 4% and 9% for G_n=100psi (0.69MPa) and G_n=200psi (1.38MPa) rubber material, respectively. Shear modulus values computed from the combined compression and shear tests were found to be only 3% higher than the shear modulus values computed from the simple shear tests. In conclusion, the shear modulus value of a NR block is not affected by an increase in the compressive stress.

6.3 Recommendations for Future Research

Test specimen sizes used to measure the mechanical properties of elastomeric materials should be representative of the full scale elastomeric bearings. Therefore, very small specimen sizes should not be used since they overestimate the material properties. When ordering elastomers by shear modulus, it is recommended that the type of shear modulus test, including specimen sizes, rate of testing, and method of measuring the shear modulus values be specified. Since the hardness measurement is not a true mechanical property of an elastomeric bearing, the shear modulus value should be specified when placing an order. The hardness measurement should be used only as a tool to help identify the type of elastomer and not as a design aid. Furthermore, even though it is well documented that Poisson's ratio for rubber is close to 0.5, which makes the relationship of Young's modulus to shear modulus 3:1, it should be understood by the design engineers that this relationship is only true for highly elastic rubbers. For hard elastomers, ratios of 4 or 5 are possible. When the value of Young's modulus, E, is encountered in design, it is recommended that either a test be performed to determine the value of E, or that the exact relationship between G and E from Figure 3.8 be used.

At shear strains of about 100%, the 0.25in. (6mm) steel plates that were used in the construction of the shear specimens started bending. This did not affect the test results since all the shear modulus values were measured at 50% shear strains. In order to reduce the bending effects at high strains thicker steel plates should be used. Concerning the compression tests, in order to eliminate any edge effects like the ones shown in Figure 5.11, it is recommended that the steel plates used in the construction of the compression specimens have the same overall dimensions as the rubber specimens.

All NR blocks used in this research had a shape factor of about "1". In order to determine if the shape factor of an elastomeric bearing has an effect on the shear modulus value, rubber blocks with a number of shape factors should be tested. Additional research can be performed on steel laminated rubber blocks to investigate the effect of reinforcement on the shear behavior. The natural rubber material used in this research was obtained from one supplier only. It is worthwhile to look into the scatter, if any, of the mechanical properties of similar elastomers that are obtained from different rubber suppliers.

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