Technical Report Documentation Page

1. Report No. FHWA-TX-96/1304-2	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle TEST METHODS FOR ELASTOMERIC BEARINGS ON BRIDGES		5. Report Date November 1995 6. Performing Organization Code
7. Author(s) Y. J. Arditzoglou, J. A. Yura, and A. H. Haines		8. Performing Organization Report No. Research Report 1304-2
9. Performing Organization Name and Address Center for Transportation Research The University of Texas at Austin 3208 Red River, Suite 200 Austin, Texas 78712-1075		10. Work Unit No. (TRAIS) 11. Contract or Grant No. Research Study 0-1304
12. Sponsoring Agency Name and Address Texas Department of Transportation Research and Technology Transfer Office P.O. Box 5080 Austin, TX 78763-5080		13. Type of Report and Period Covered Interim 14. Sponsoring Agency Code

15. Supplementary Notes

Study conducted in cooperation with the U.S. Department of Transportation, Federal Highway Administration.
Research study title: "Elastomeric Bearings"

16. Abstract

This report discusses the material properties of elastomers for bridge bearings 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.

The ASTM quad shear test for shear modulus of elastomeric material in bridge bearings was evaluated by comparing the shear modulus from the ASTM test method with the results of full-size bearings manufactured from the same material. The comparison showed that the ASTM test can give significantly different results from the full-size tests; the difference depends on the size of the quad shear test specimen, the method of attachment and testing the full-size specimen, and the method of determining the shear modulus from the quad shear test. The ASTM quad shear test gave poor correlation with the full-size test when high hardness materials were used.

17. Key Words Bridges, design, behavior, bearings, elastomers, neoprene, rubber	18. Distribution Statement No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161.

19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 106	22. Price

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TEST METHODS FOR ELASTOMERIC BEARINGS ON BRIDGES

by

Y. J. Arditzoglou,
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and
A. H. Haines

Research Report 1304-2

Research Project 0-1304
"Elastomeric Bearings"

conducted for the

TEXAS DEPARTMENT OF TRANSPORTATION

in cooperation with the

U.S. Department of Transportation
Federal Highway Administration

by the

CENTER FOR TRANSPORTATION RESEARCH
Bureau of Engineering Research
THE UNIVERSITY OF TEXAS AT AUSTIN

November 1995

IMPLEMENTATION STATEMENT

The research showed that the current ASTM method of obtaining shear modulus of elastomeric materials for bridge bearings is not reliable (does not compare well with full-size bearing tests) unless a particular size ASTM specimen is chosen, adjustment made for bearings not permanently attached to the abutments and girders (most Texas bearings fall into this category), and/or the method of calculating the shear modulus from the test is altered. Therefore, the shear modulus method of specifying the material in the bridge bearing is not recommended at this time. An NCHRP project on the test methods for elastic bearings was planned for 1996 but has now been put off. This project should go forward. It is recommended that bridge bearings continue to be specified according to durometer hardness until the test methods for shear modulus become reliable.

Prepared in cooperation with the Texas Department of Transportation
and the U.S. Department of Transportation, Federal Highway Administration

DISCLAIMERS

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SUMMARY

This report discusses the material properties of elastomers for bridge bearings 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 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, 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. 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.

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 and to compare these results with shear modulus values obtained from full scale tests performed in a different manner. This initial study of the shear modulus indicated a significant different in the measured values between the different test methods and additional shear modulus tests were conducted to quantify this difference.

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 4 of this report. Tests were carried out at room temperature on bnded 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 100 psi (0.69 MPa) and 200 psi (1.379 MPa). Load deformation relationships were obtained from all tests and mechanical properties such as E_c, tensile modulus, E_t, and G values were determined. Additional tests, presented in Chapter 6, were conducted in the same manner on specimens that varied in sizes of 2 x 2 x 1 in. (50.8 x 50.8 x 25.4 mm), 4 x 4 x 1 in. (101.6 x 101.6 x 25.4 mm), and 6 x 6 x 1 in. (152.4 x 152.4 x 25.4 mm). Full scale tests were conducted on specimens measuring 9 x 14 in. (229 x 356 mm) with an elastomer thickness of 1.75 in. (44.5 mm).

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.

2.1.1.1 Compounding:

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

Figure 2- 1 Rubber is worked on the mixing mill

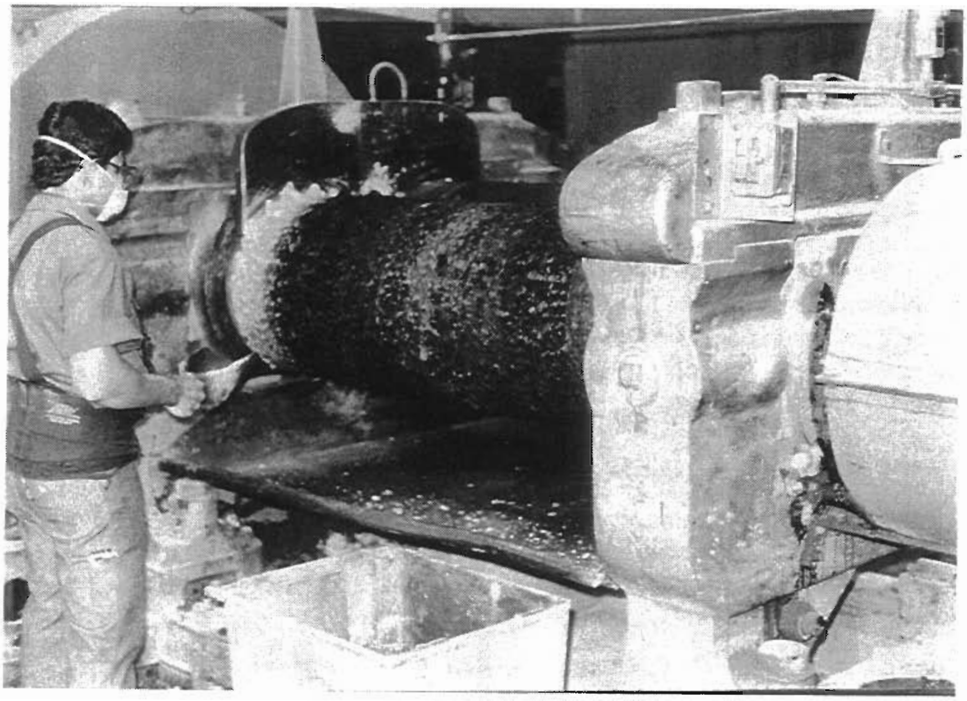


Figure 2- 2 Chemical ingredients are added to the rubber band

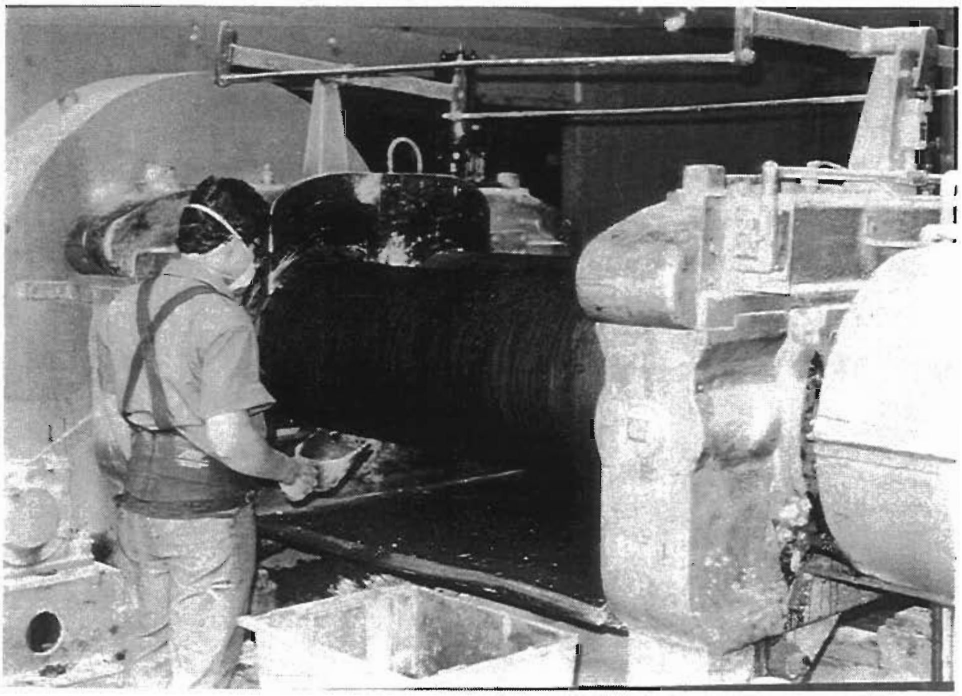


Figure 2- 3 Carbon black filler is added to the rubber band

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.

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°F (140-150°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).

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).

The vulcanization or curing of the compounded rubber is usually carried out under pressure in metal molds at a temperature of about 284°F (140°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.

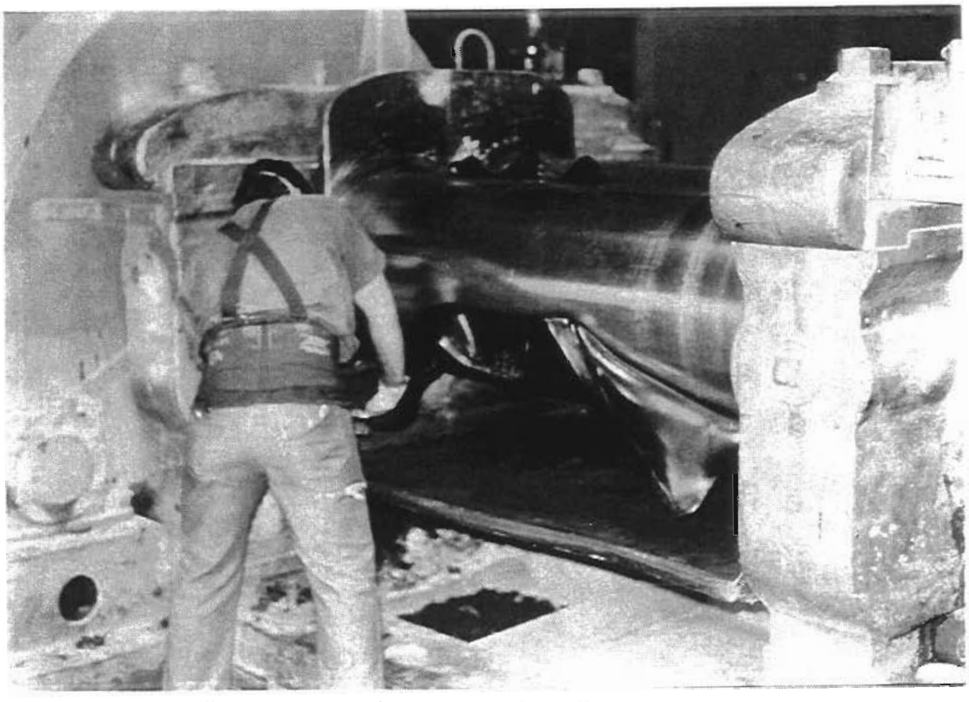


Figure 2- 4 The rubber band is cut from the mill

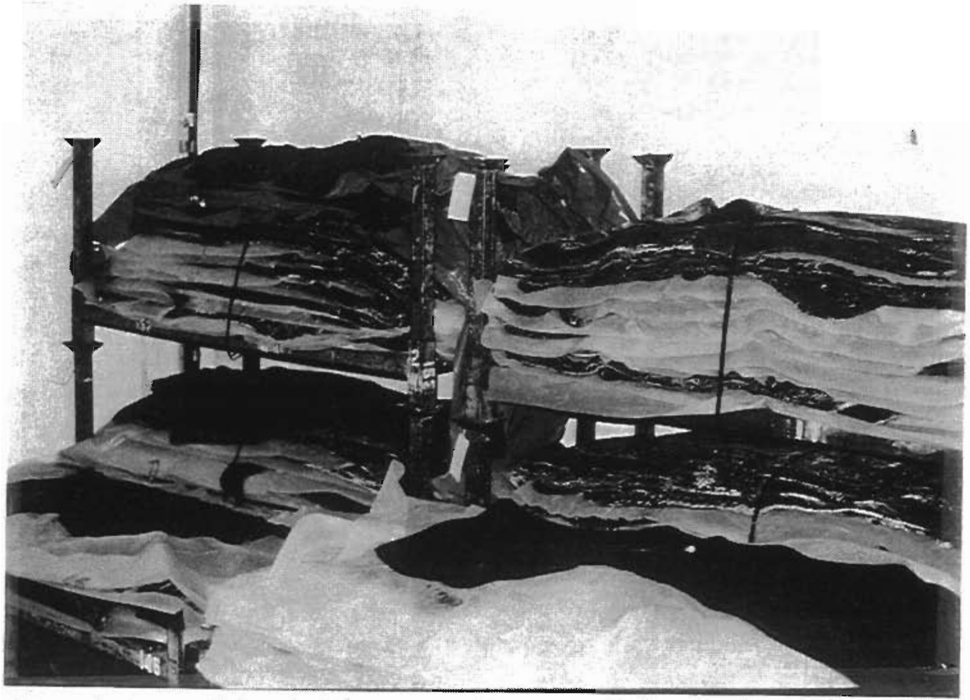


Figure 2- 5 *Slabs of rubber are stored in a controlled temperature and humidity*

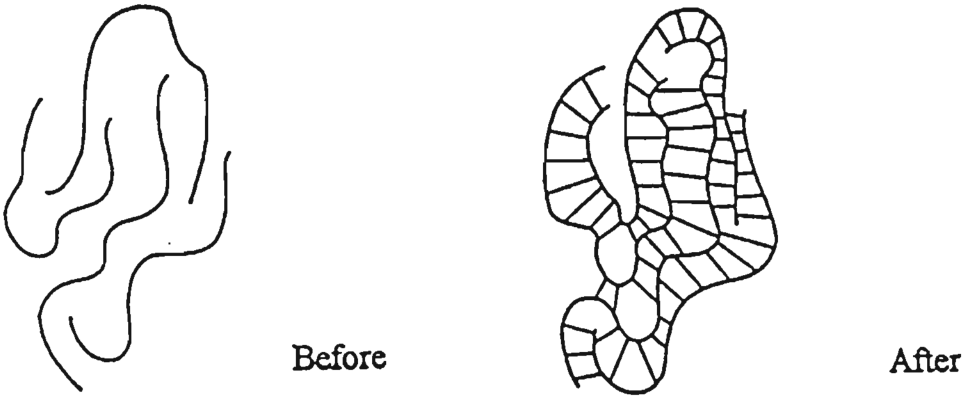
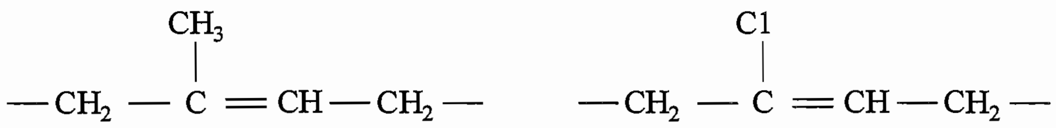


Figure 2- 6 *Rubber before and after vulcanization*



$$-\mathrm{CH_2}-\overset{\mathrm{CH_3}}{\overset{|}{\mathrm{C}}}=\mathrm{CH}-\mathrm{CH_2}- \qquad -\mathrm{CH_2}-\overset{\mathrm{Cl}}{\overset{|}{\mathrm{C}}}=\mathrm{CH}-\mathrm{CH_2}-$$

Figure 2- 7 *Structural formulas for polyisoprene and polychloroprene (40)*

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 ¼ and 1/3.

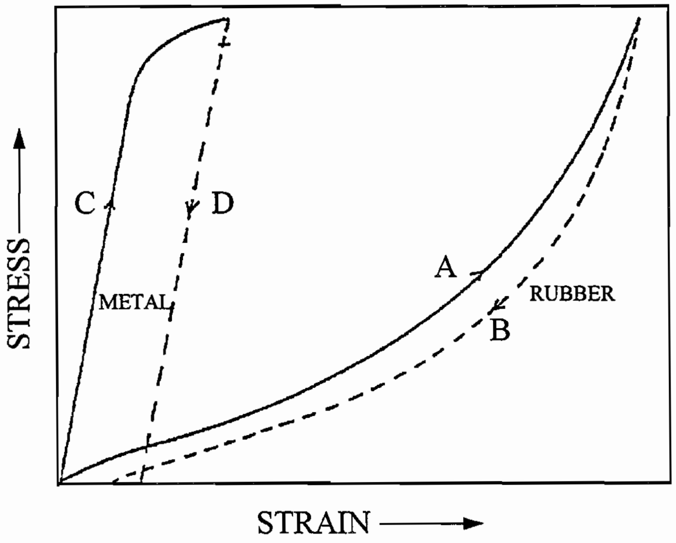


Figure 2- 8 *Stress-strain curves for loading and unloading of rubber and metals (3)*

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).

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.

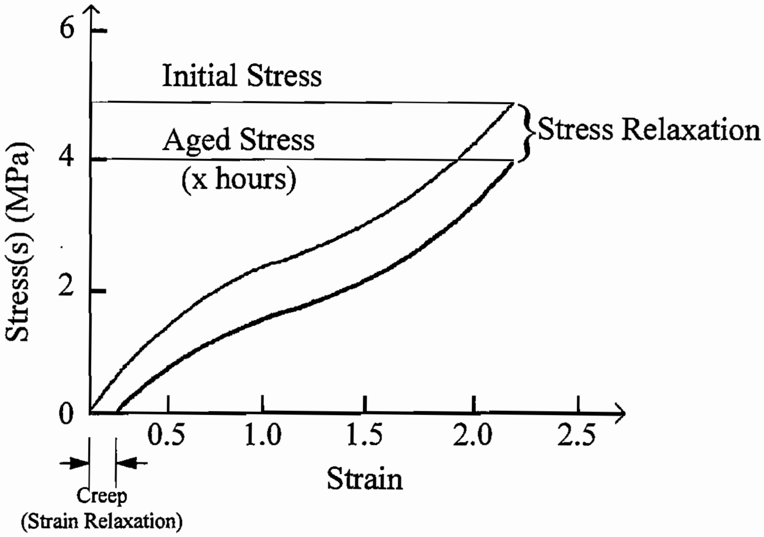


Figure 2- 9 Stress and strain (creep) relaxation to elastomers (5)

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).

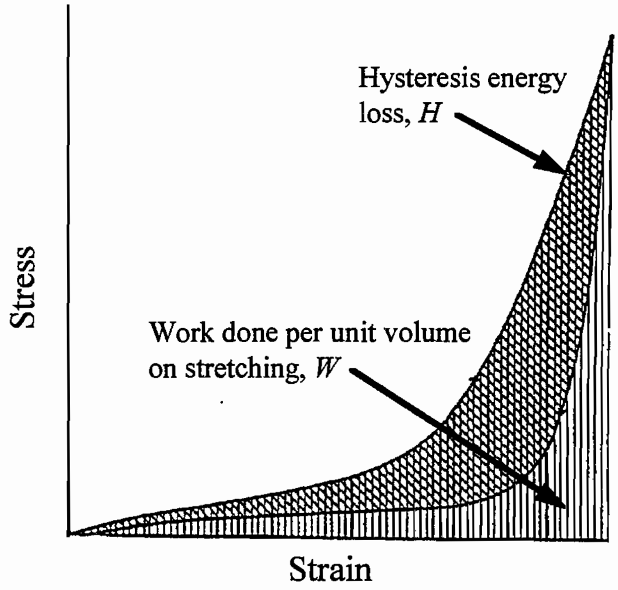


Figure 2- 10 *Typical stress-strain loading-unloading cycle of rubber (8)*

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).

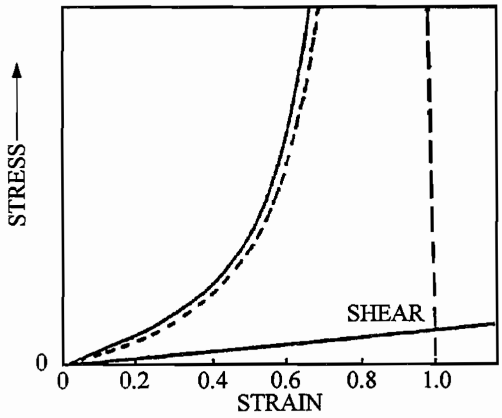


Figure 2- 11 *Comparison of stress-strain curves of rubber in compression and shear (3)*

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.

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

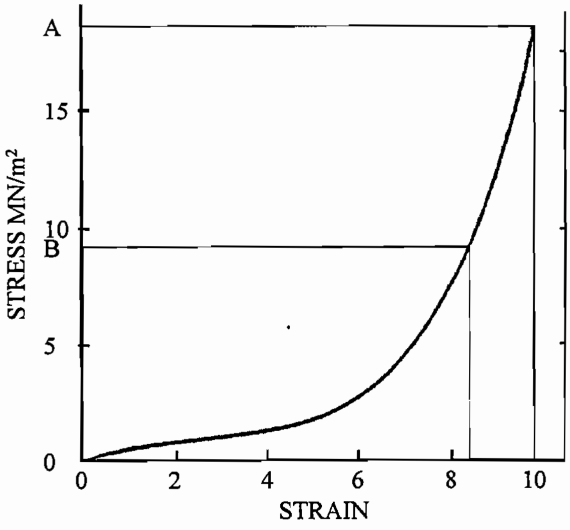


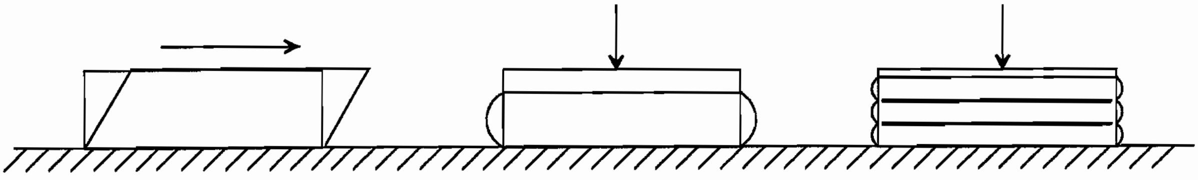
Figure 2- 12 Tensile stress-strain curve for rub-

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

(a) Plain Pad (b) Reinforced Pad



(c) Shear Deformation (d) Plain Pad Under Compression (e) Reinforced Pad Under Compression

Figure 2- 13 Plain and reinforced elastomeric bearings

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).

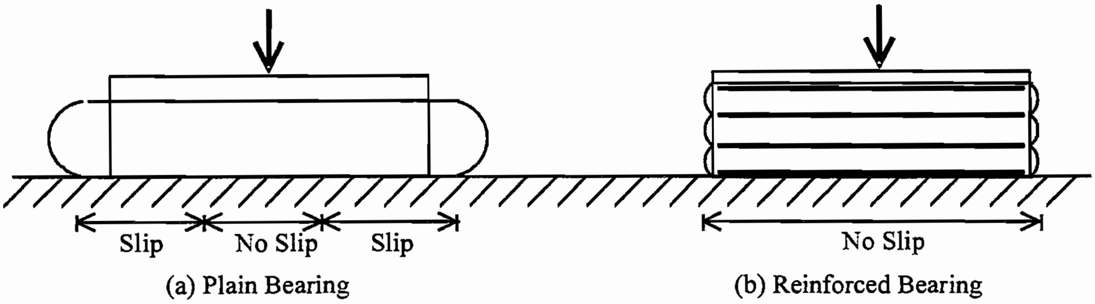
2.2.1 FAILURE MODES: REASONS AND REMEDIES

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).

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



(a) Plain Bearing

(b) Reinforced Bearing

Figure 2- 14 Slip phenomenon in plain and reinforced bearings

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 2.15 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%.

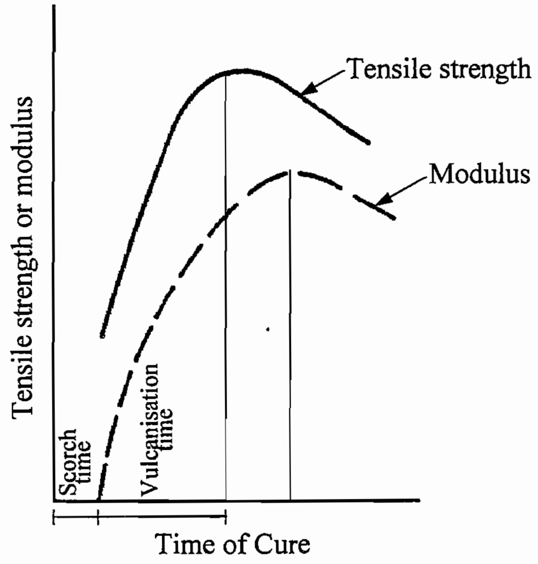


Figure 2- 15 Effect of vulcanization time on the tensile strength and modulus of NR (8)

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:

<u>Plain:</u> 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.

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.

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°F (-7°C) to the values given is Table 2.4.

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- 1   Physical properties of Neoprene 1961 AASHTO (17)

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

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

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

Table 2- 5 Dimension tolerances for elastomeric bearings 1977 and 1983 AASHTO (20, 21)

1) Overall Vertical Dimensions	
Average Total Thickness	
1 ¼” (31.8mm) or less	-0, +1/8in. (3mm)
Average Total Thickness	
over 1 ¼” (31.8mm)	-0, +1/4in. (6mm)
(2) Overall Horizontal Dimension	
36in. (914mm) and less	-0, +1/4in. (6mm)
over 36in. (914mm)	-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	1/8in. (3mm)
Individual Nonelastic Laminates	1/4in. (6mm)
	1/8in. (3mm)
(5) Position of Exposed	1/8in. (3mm)
Connection Members	
(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)

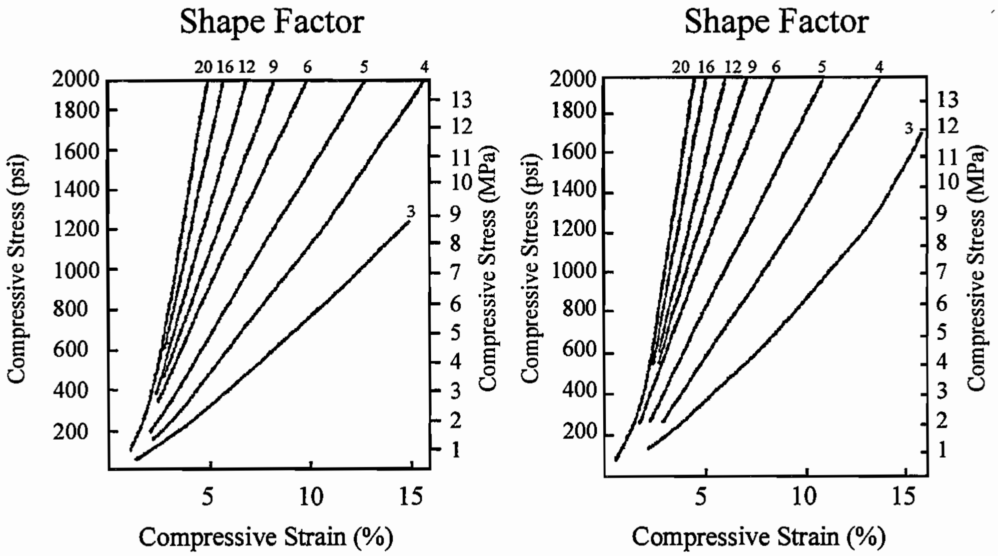
Hardness (Shore"A")	50	60	70
Shear Modulus at 73F (23C) psi (MPa)	85-110 (0.60-0.77)	120-155 (0.85-1.10)	160-260 (1.10-1.79)
creep deflection instantaneous deflection at 25 years	25%	35%	45%

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



50 DUROMETER 60 DUROMETER

Figure 2- 16 Compressive stress-strain curves for 50 and 60 durometer elastomers (22)

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.

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:

$$L\alpha_L + W\alpha_W \le 2\Delta_c \qquad \text{for rectangular pads}$$

$$D\,(\alpha_L{}^2 + \alpha_W{}^2)^{1/2} \le 2\Delta_c \qquad \text{for circular pad}$$

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.

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.

Table 2- 7 Dimension tolerances for elastomeric bearing 1989 (AASHTO (22)

(1)	Overall Vertical Dimensions	
	Average Total Thickness 1 ¼" (32mm) or less	-0, +1/8in. (3mm)
	Average Total Thickness over 1 ¼" (32mm)	-0, +1/4in. (6mm)
(2)	Overall Horizontal Dimension	
	36in. (0.914m) and less	-0, +1/4in. (6mm)
	over 36in. (0.914m)	**-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	**slope relative to the bottom of no more than 0.005 radian**
	Sides	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 to 1983 AASHTO specifications

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°F (23°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°F (0°C). These values are given in Table 2.9.

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 ©	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

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.

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

$\sigma_{c,TL} \le GS/\beta$, 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

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:

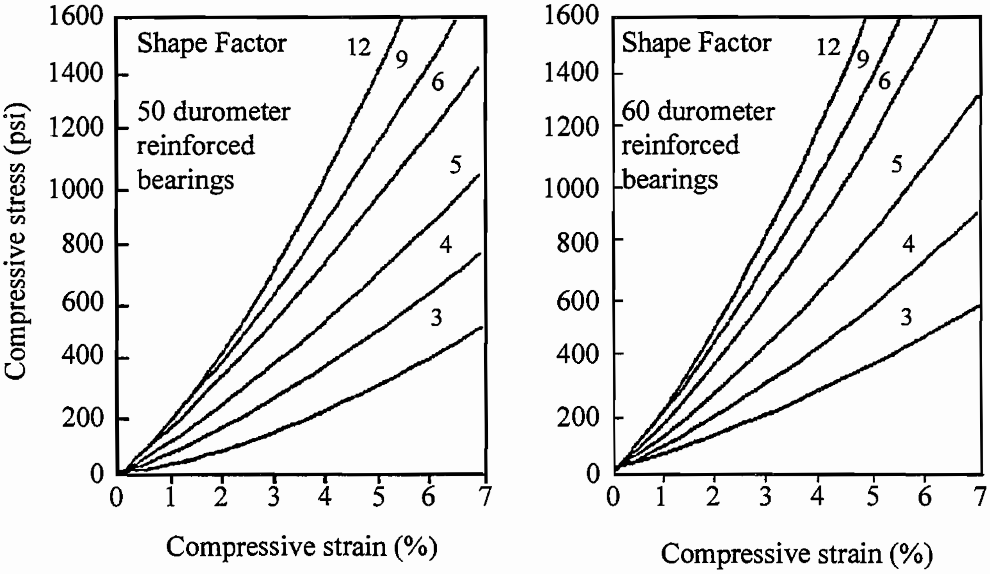


Figure 2- 17 Compressive stress-strain curves for 50 and 60 durometer elastomers (24)

$$\sigma_{c,TL} \le \frac{1.66GS/\beta}{1+\dfrac{L\theta_{TL,x}}{4\Delta_c}}$$ for bearings subject to shear deformations

$$\sigma_{c,TL} \le \frac{2.0GS/\beta}{1+\dfrac{L\theta_{TL,x}}{4\Delta_c}}$$ 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:

$$\sigma_{c,TL} \le G \Big/ \left\{ \frac{3.84(h_{rt}/L)}{S\sqrt{1+2L/W}} - \frac{2.67}{S(S+2)(1+L/4W)} \right\}$$ if the bridge is free to translate horizontally, or

$$\sigma_{c,TL} \le G \Big/ \left\{ \frac{1.92(h_{rt}/L)}{S\sqrt{1+2L/W}} - \frac{2.67}{S(S+2)(1+L/4W)} \right\}$$ 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.

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%.

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°F (-7°C), 0°F (-18°C), and -20°F (-29°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- 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 ¾ cycle of strain shall be disregarded and the stiffness shall be determined by the slope of the force deflection curve for the next ½ cycle of loading.		

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 ¾ cycle of strain shall be disregarded and the stiffness shall be determined by the slope of the force deflection curve for the next ½ cycle of loading.		

Table 2- 12 Dimension tolerances for elastomeric bearings - 1992 AASHTO (24)

1) Overall Height Design Thickness 1 ¼” (32mm) or less Design Thickness over 1 ¼” (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*

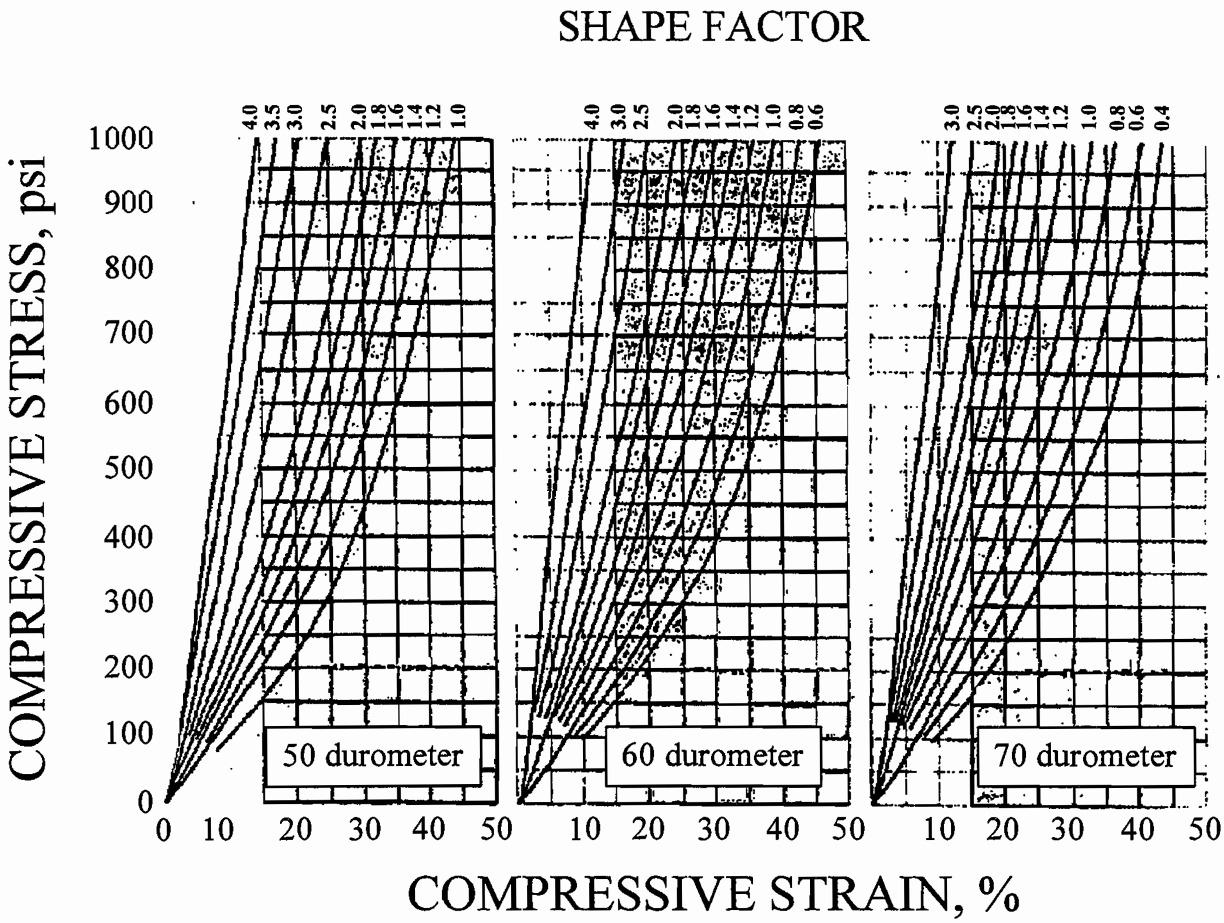


Figure 2- 18 Compression curves for 50, 60, and 70 durometer hard neoprene (11)

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,

σ_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

Table 3- 1 Compressive stiffness factors for various cross sections (28)

Cross-Section	f_{c1}	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

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

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:

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

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.

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+v)) 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.

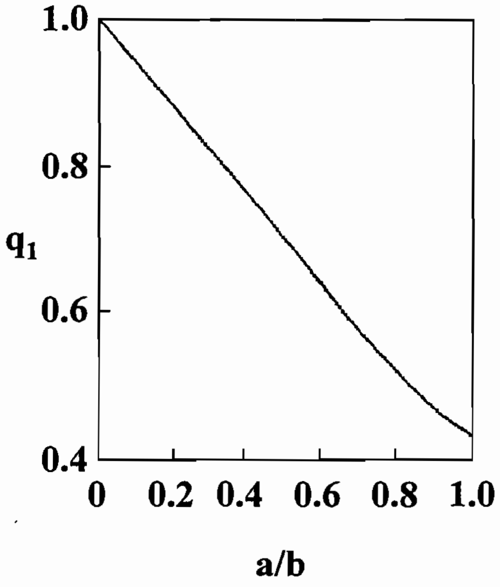


Figure 3- 1 *Compression stiffness factor q_1 for rectangular cross section (28)*

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).

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.

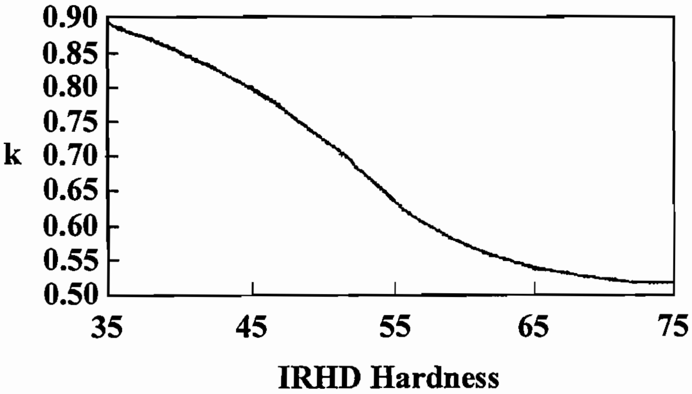


Figure 3- 2 *Material constant k as a function of hardness (31)*

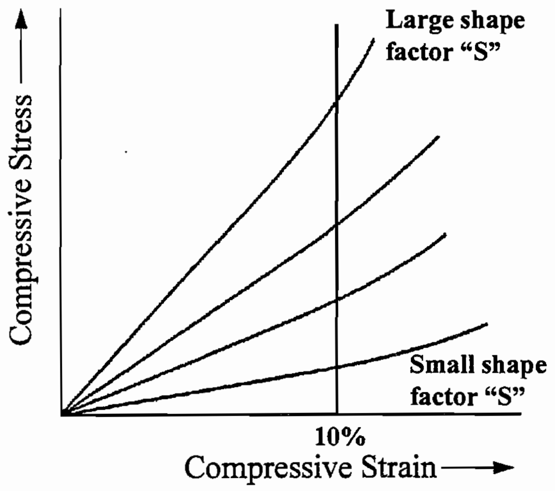


Figure 3- 3 *Compressive stress-strain curves as a function of shape factor S (3)*

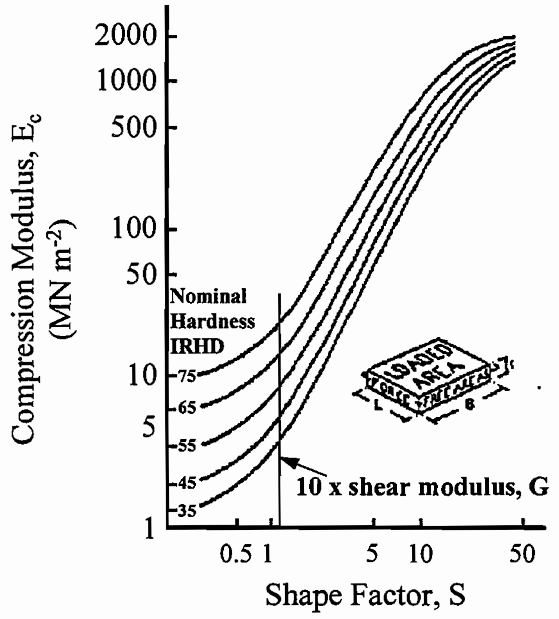


Figure 3- 4 *Variation of compressive modulus E_c with S and Hardness (7)*

3.3.1 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.

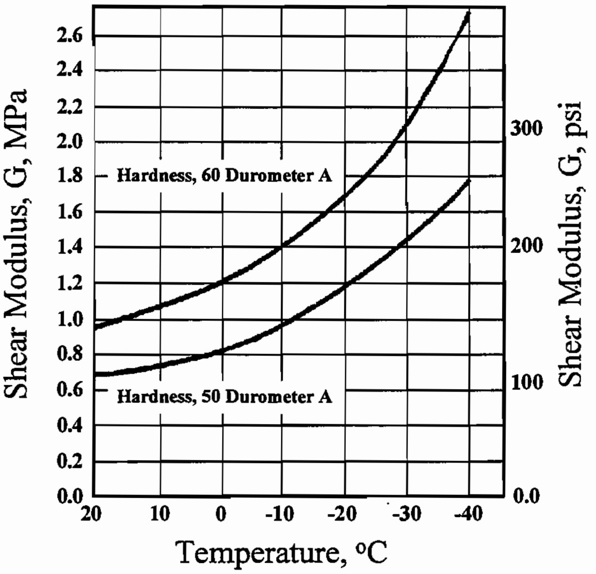


Figure 3- 5 Relationship of G to hardness of Neoprene at various temperatures (8)

3.3.2.1 Determination of Shear Modulus

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).

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° (0.268) and tan 30° (0.577) in the calculation of the shear modulus (see Figure 3.6b).

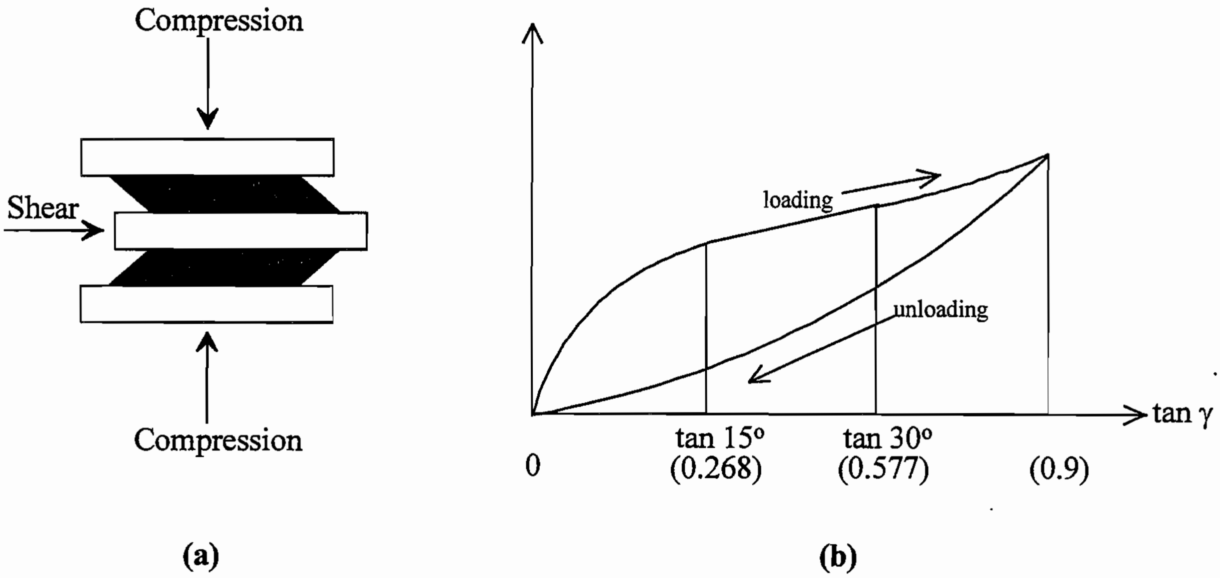


Figure 3- 6 *(a) Arrangement of bearings and concrete slabs; (b) Loading-unloading curves*

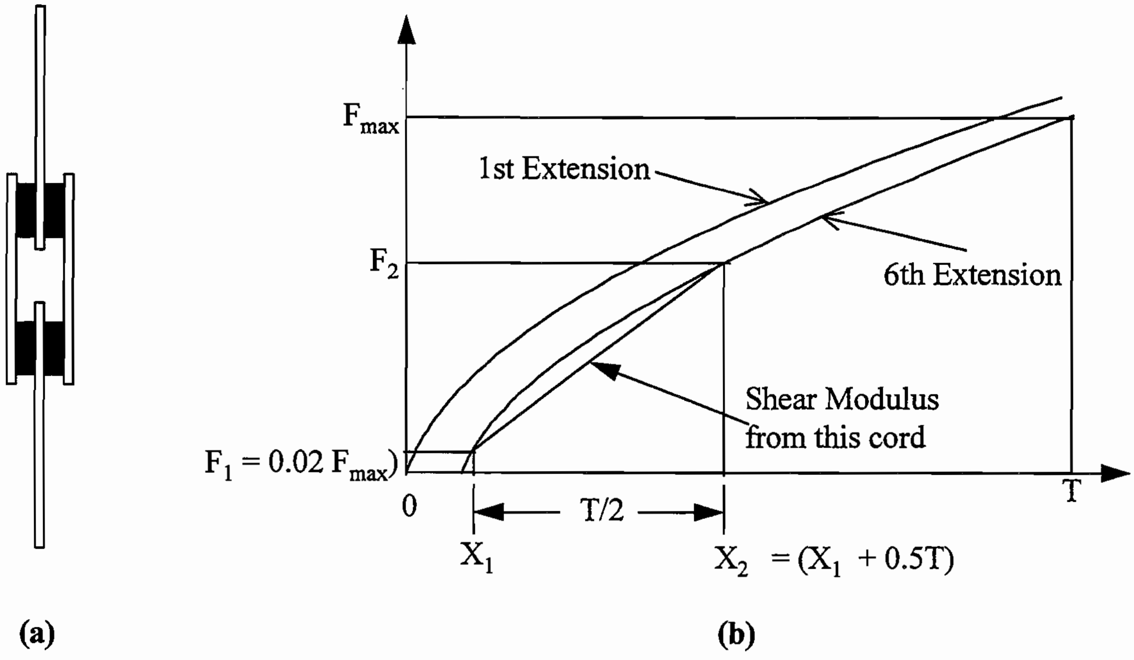


Figure 3- 7 *(a) Quadruple shear test piece; (b) 1st and 6th load-deflection curves*

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).

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

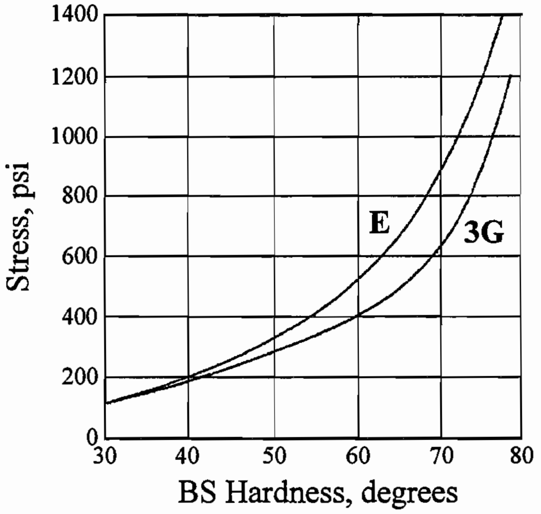


Figure 3- 8 *Relations between Young's Modulus E, shear modulus G, and Hardness (3)*

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

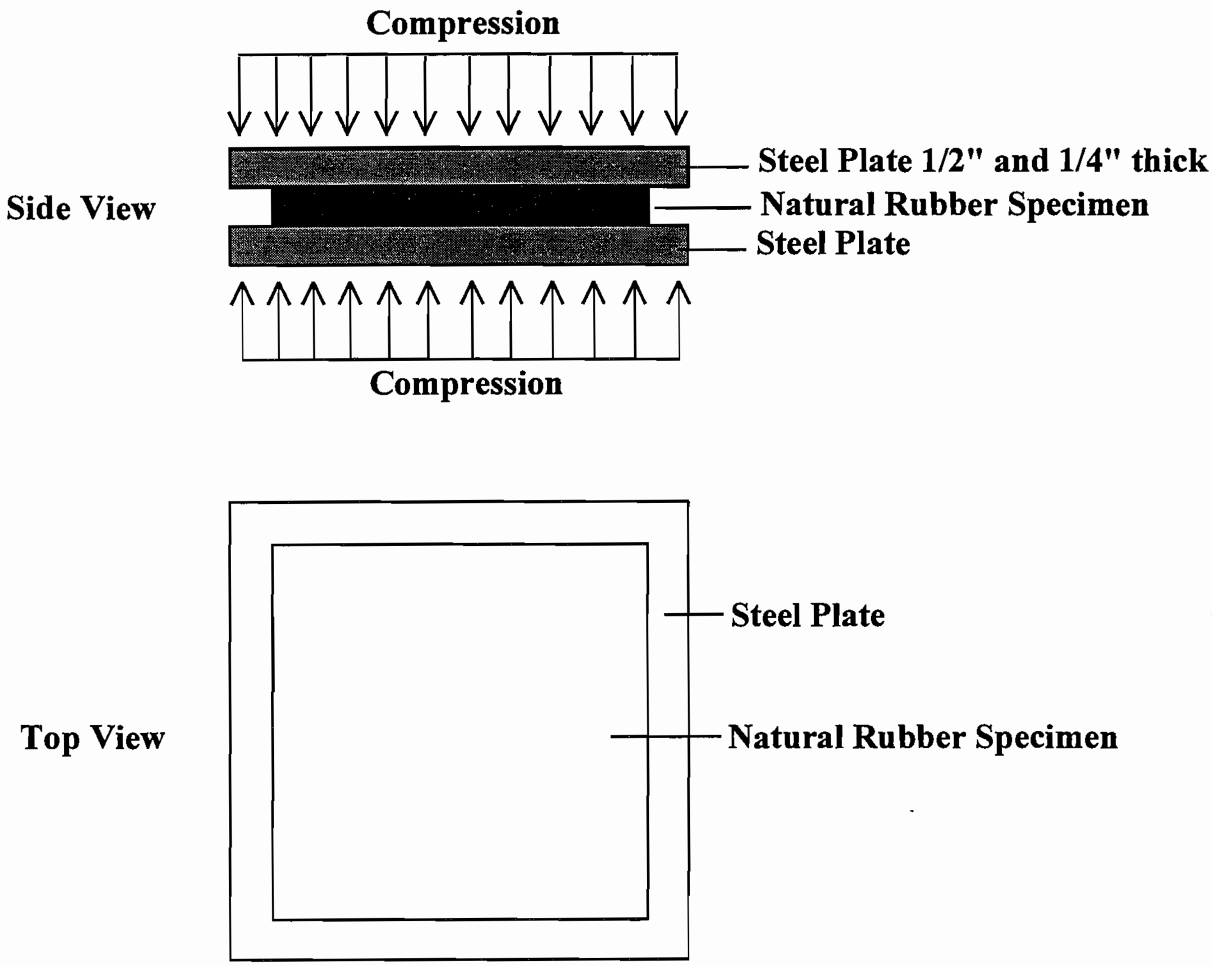


Figure 4- 1 *Compression test setup*

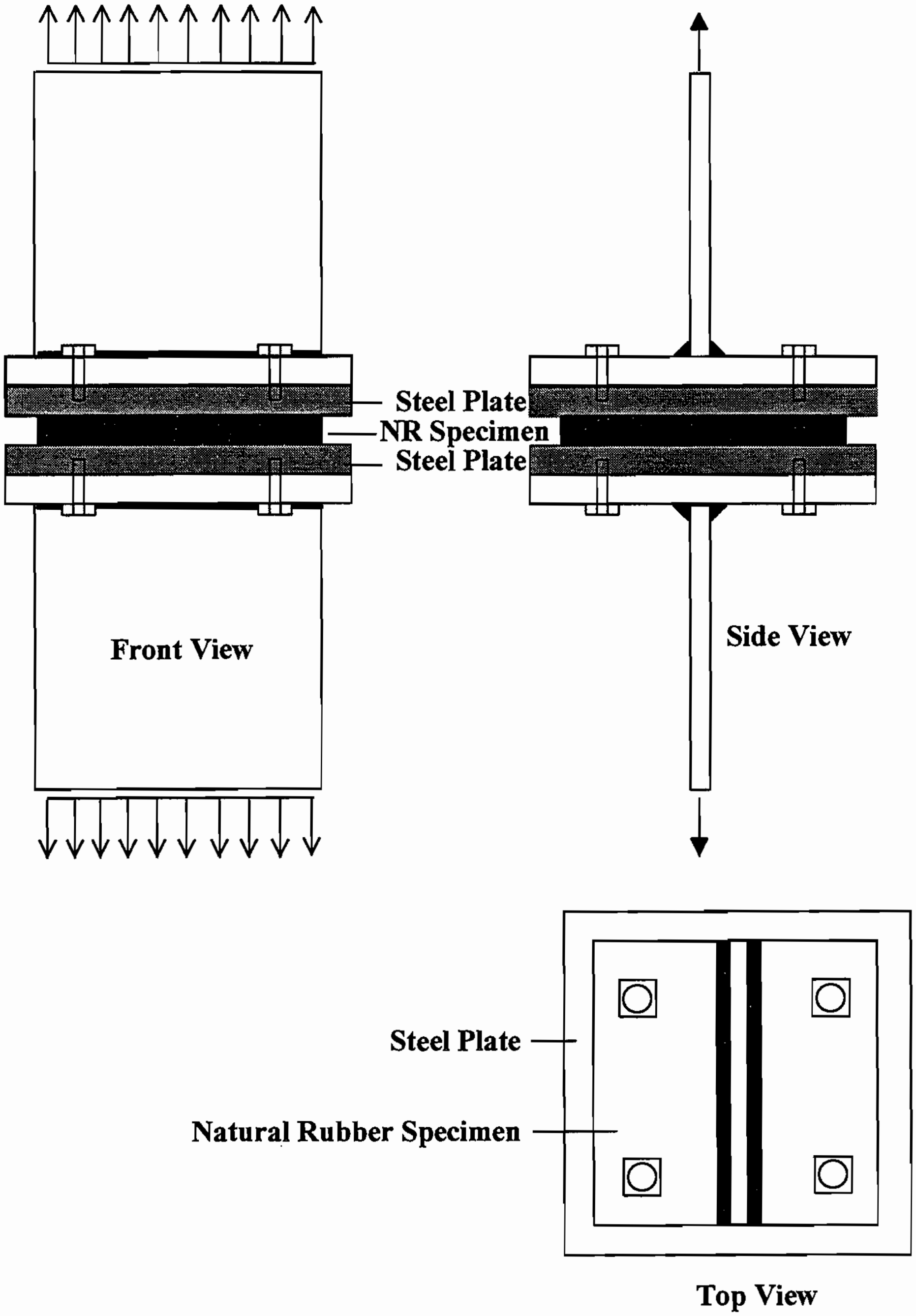


Figure 4- 2 *Tension test setup*

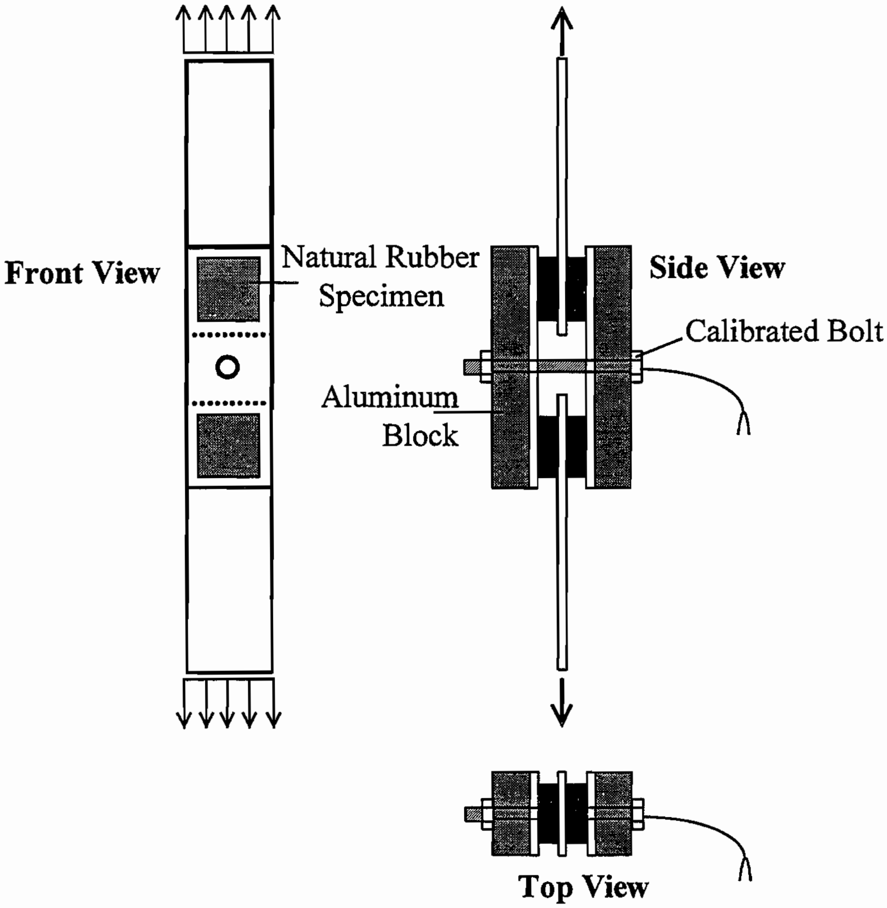


Figure 4- 3 *Combined compression and shear test setup*

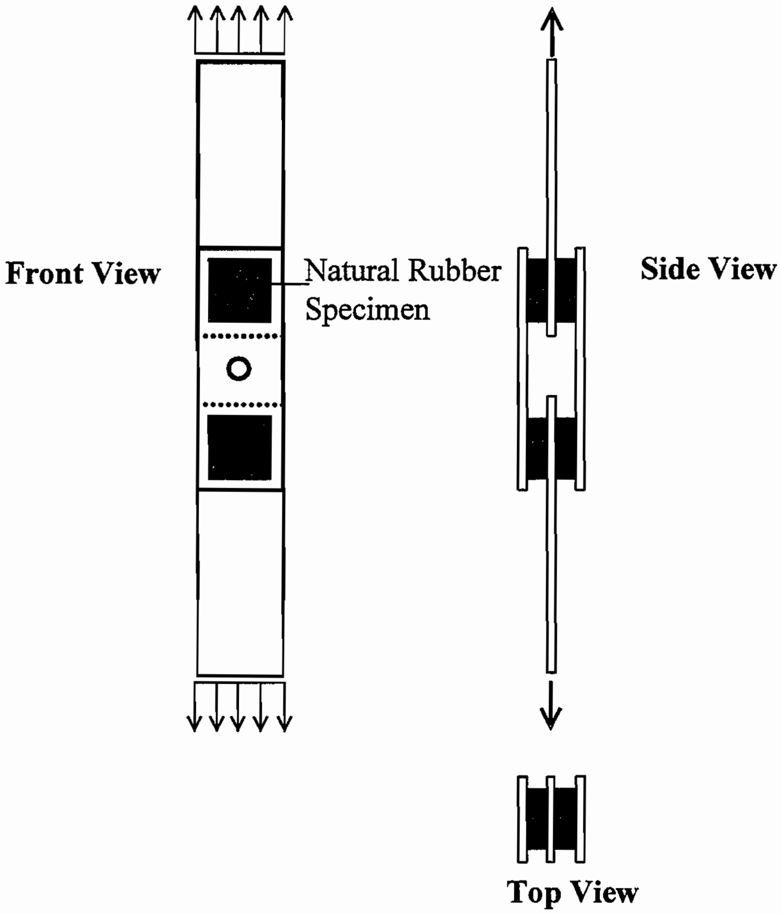


Figure 4- 4 *Shear test setup*

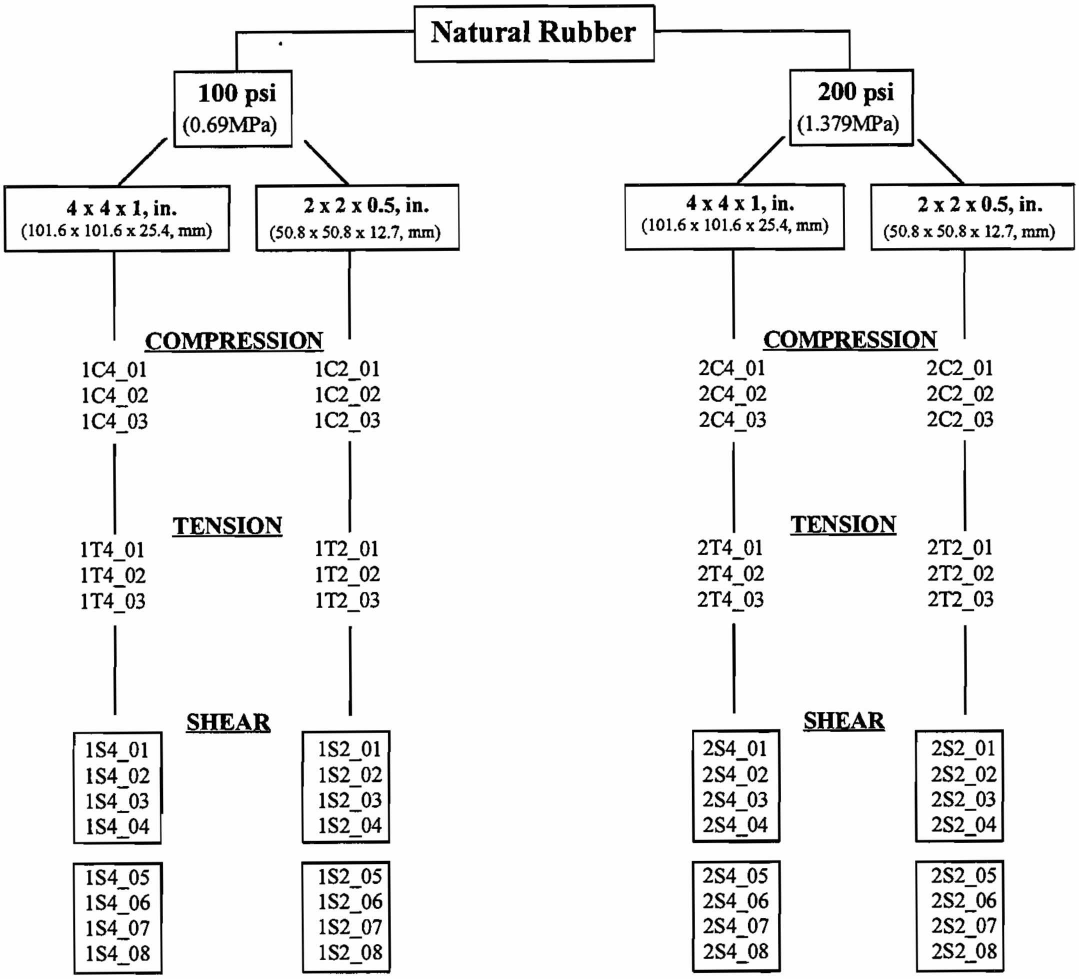


Figure 4- 5 *Breakdown of the NR specimens used in the test program*

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.

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°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

Table 4- 1 Physical Properties

(a) Physical Properties of the Compression

Specimen Number	G (psi)	Hardness (Shore A)	Average Length (in.)	Average Width (in.)	Average Thickness (in.)	Area (in.)	Shape Factor
1C4-01	100	61.0	3.892	3.965	1.067	15.432	0.920
1C4-02	100	61.5	3.994	4.036	1.054	16.120	0.952
1C4-03	100	59.0	4.007	3.957	1.065	15.856	0.935
2C4-01	200	67.0	3.951	3.978	1.065	15.717	0.931
2C4-02	200	68.0	3.962	3.901	1.080	15.456	0.910
2C4-03	200	70.0	3.956	3.870	1.130	15.310	0.866
1C2-01	100	62.5	1.986	1.995	0.529	3.962	0.941
1C2-02	100	61.0	1.958	1.989	0.570	3.894	0.866
1C2-03	100	60.5	2.004	1.958	0.550	3.924	0.900
2C2-01	200	69.0	1.968	1.995	0.530	3.926	0.935
2C2-02	200	67.0	1.989	1.968	0.540	3.914	0.916
2C2-03	200	68.0	2.000	2.205	0.540	4.410	0.971

(b) Physical Properties of the Tension Specimens

Specimen Number	G (psi)	Hardness (Shore A)	Average Length (in.)	Average Width (in.)	Average Thickness (in.)	Area (in$^{2.}$)	Shape Factor
1T4-01	100	61.0	3.991	3.990	1.085	15.924	0.919
1T4-02	100	60.0	3.905	3.913	1.082	15.280	0.903
1T4-03	100	61.5	4.030	3.960	1.073	15.959	0.931
2T4-01	200	70.0	3.860	3.935	1.098	15.189	0.887
2T4-02	200	69.0	3.860	3.950	1.095	15.247	0.891
2T4-03	200	67.5	3.893	3.935	1.078	15.319	0.908
1T2-01	100	58.0	2.058	1.988	0.499	4.091	1.013
1T2-02	100	60.0	1.960	1.957	0.500	3.836	0.979
1T2-03	100	56.0	2.050	1.985	0.543	4.069	0.929
2T2-01	200	67.0	2.070	2.040	0.550	4.223	0.934
2T2-02	200	70.0	2.020	2.016	0.491	4.072	1.027
2T2-03	200	70.0	1.988	1.920	0.540	3.817	0.904

Table 4.1 Physical Properties (continued)

(c) Physical Properties of the Shear Specimens

Specimen Number	G (psi)	Hardness (Shore A)	Average Length (in.)	Average Width (in.)	Average Thickness (in.)	Area (in.)	Shape Factor
1S4-01	100	63.5	3.897	3.957	1.074	15.420	0.914
1S4-02	100	62.5	4.057	3.885	1.084	15.761	0.915
1S4-03	100	59.0	3.968	3.958	1.085	15.705	0.913
1S4-04	100	62.0	3.991	4.020	1.072	16.044	0.934
1S4-05	100	63.5	4.020	3.915	1.065	15.738	0.931
1S4-06	100	62.5	3.922	3.935	1.070	15.433	0.918
1S4-07	100	62.5	3.937	4.038	1.071	15.898	0.931
1S4-08	100	61.0	3.894	3.856	1.083	15.015	0.894
2S4-01	200	70.0	3.892	3.978	1.113	15.482	0.884
2S4-02	200	66.0	3.935	3.978	1.073	15.653	0.922
2S4-03	200	70.5	4.015	3.955	1.106	15.879	0.901
2S4-04	200	69.5	3.988	3.884	1.106	15.489	0.890
2S4-05	200	70.5	3.957	3.900	1.107	15.432	0.887
2S4-06	200	70.0	3.927	4.024	1.109	15.802	0.896
2S4-07	200	69.5	3.930	3.958	1.106	15.555	0.891
2S4-08	200	67.0	3.970	3.955	1.079	15.701	0.918
1S2-01	100	60.0	2.036	1.995	0.496	4.062	1.016
1S2-02	100	59.0	1.959	1.984	0.530	3.887	0.930
1S2-03	100	59.5	1.996	2.034	0.520	4.060	0.969
1S2-04	100	59.0	1.949	2.010	0.530	3.917	0.934
1S2-05	100	60.0	1.976	1.968	0.526	3.889	0.937
1S2-06	100	60.0	1.943	1.988	0.542	3.863	0.906
1S2-07	100	63.0	2.002	2.072	0.524	4.148	0.972
1S2-08	100	60.0	2.040	1.970	0.546	4.019	0.918
2S2-01	200	70.0	1.963	2.022	0.515	3.969	0.967
2S2-02	200	69.0	1.952	2.003	0.540	3.910	0.915
2S2-03	200	68.0	1.994	2.000	0.548	3.988	0.911
2S2-04	200	70.0	1.959	1.980	0.595	3.879	0.827
2S2-05	200	68.0	1.958	2.019	0.559	3.953	0.889
2S2-06	200	67.0	1.988	2.005	0.554	3.986	0.901
2S2-07	200	70.0	1.999	1.985	0.595	3.968	0.837
2S2-08	200	67.0	2.004	1.944	0.553	3.896	0.892

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

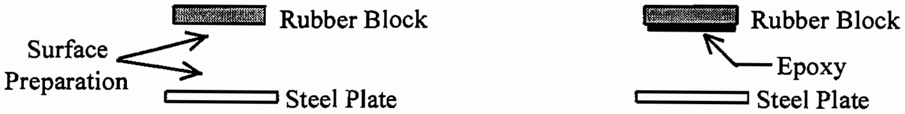
All the tests were performed at room temperature. Since all the specimens were stored at the test temperature, no special conditioning time was required before loading. The stress-strain relationship in all the tests was based on the initial (undeformed) areas and thicknesses of the NR specimens.

4.10.1 COMPRESSION TESTS

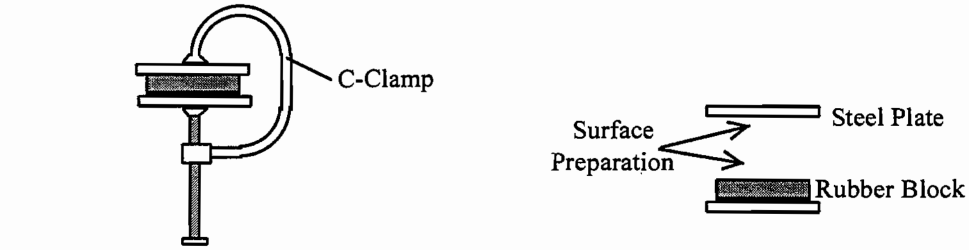
The compression tests were broken down into two parts. In part I, values of compressive modulus, E_c, were calculated at very small strains (between 4% and 8%), whereas, in part II, the effects of stress relaxation and creep (strain relaxation) were studied at various strains.

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 5^{th} loading cycle between 4% and 8% strain.

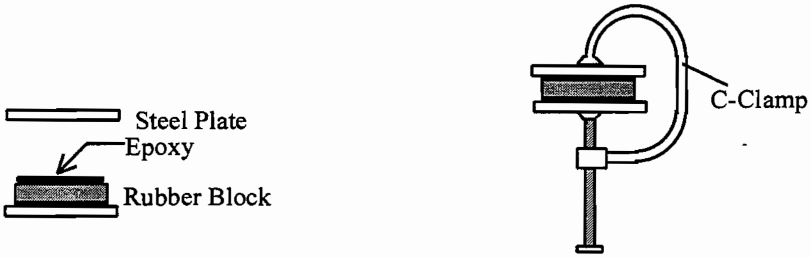
In part II of the compression tests, the 1in. (25.4mm) thick specimens were loaded at a rate of 0.02in/minute, (0.5mm/minute) up to strains corresponding to 1500psi (10.24MPa) and 7500psi (51.7MPa) compressive stresses, while the 0.5in. (12.7mm) thick specimens were loaded at the same rate up to strains 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



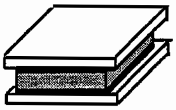
(a) Prepare surfaces **(b) Apply Epoxy on Rubber Surface**



(c) Clamp Specimen with C-clamp and wipe off Excess Epoxy **(d) Prepare Surfaces**

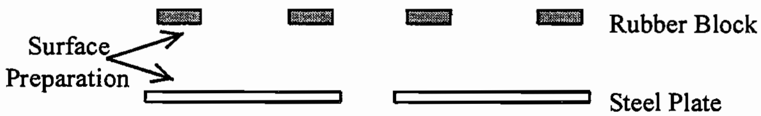


(e) Apply Epoxy on Rubber Surface **(f) Clamp Specimen with C-clamp and wipe off Excess Epoxy**

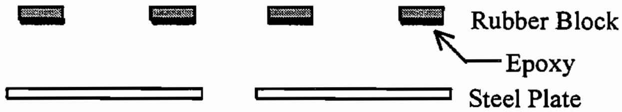


(g) Compression and Tension Specimens After the Gluing Operation

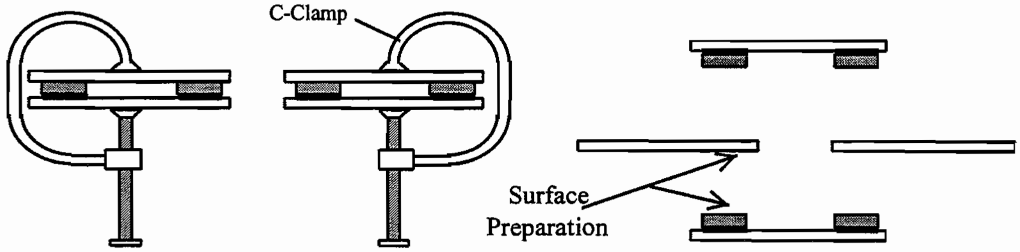
Figure 4- 6 Gluing stages of the compression and tension specimens



(a) Prepare surfaces

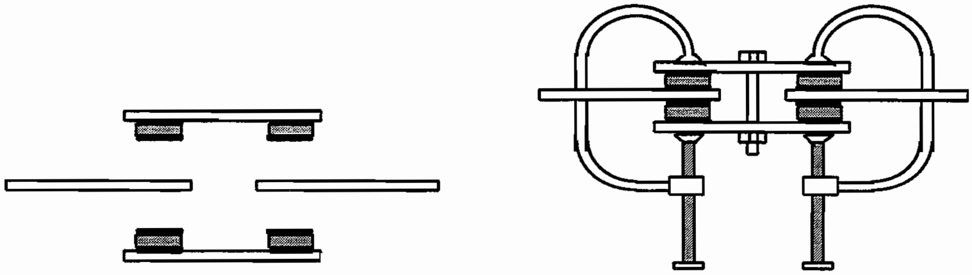


(b) Apply Epoxy on Rubber Surface



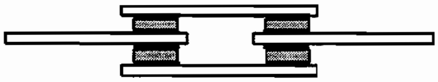
(c) Clamp Specimen with C-clamp and wipe off Excess Epoxy

(d) Prepare Surfaces



(e) Apply Epoxy on Rubber Surface

(f) Clamp Specimen with C-clamp and bolt and wipe off Excess Epoxy



(g) Shear Specimen After the Gluing Operation

Figure 4- 7 Gluing stages of the shear specimens

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.

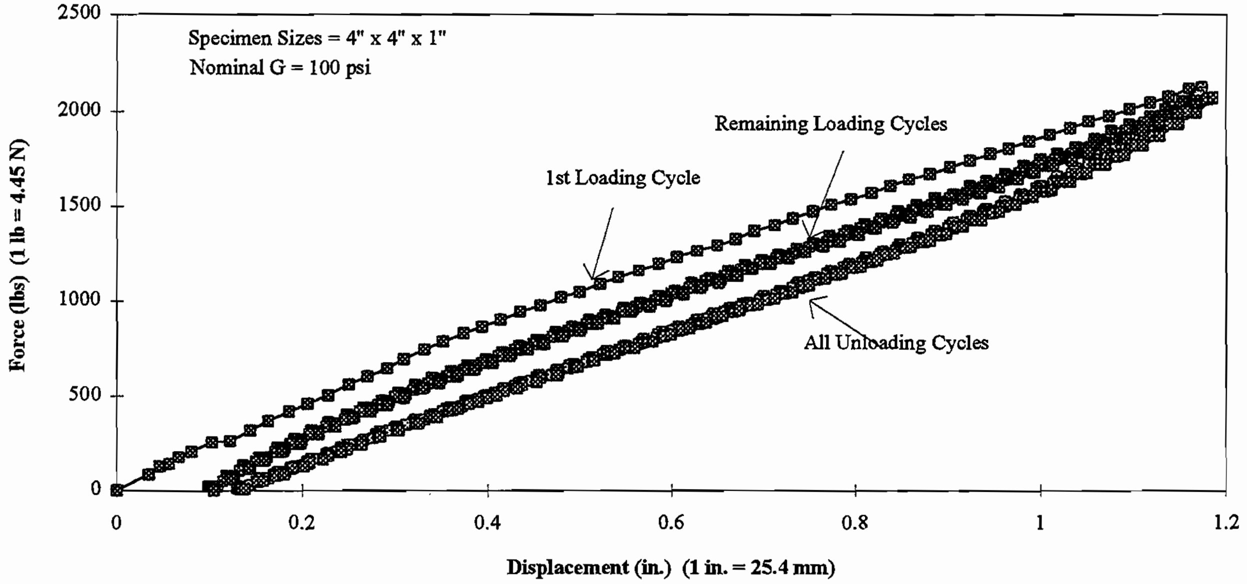


Figure 5- 1 Load-displacement cycles for the 1S4_01, 02, 03, 04 specimens

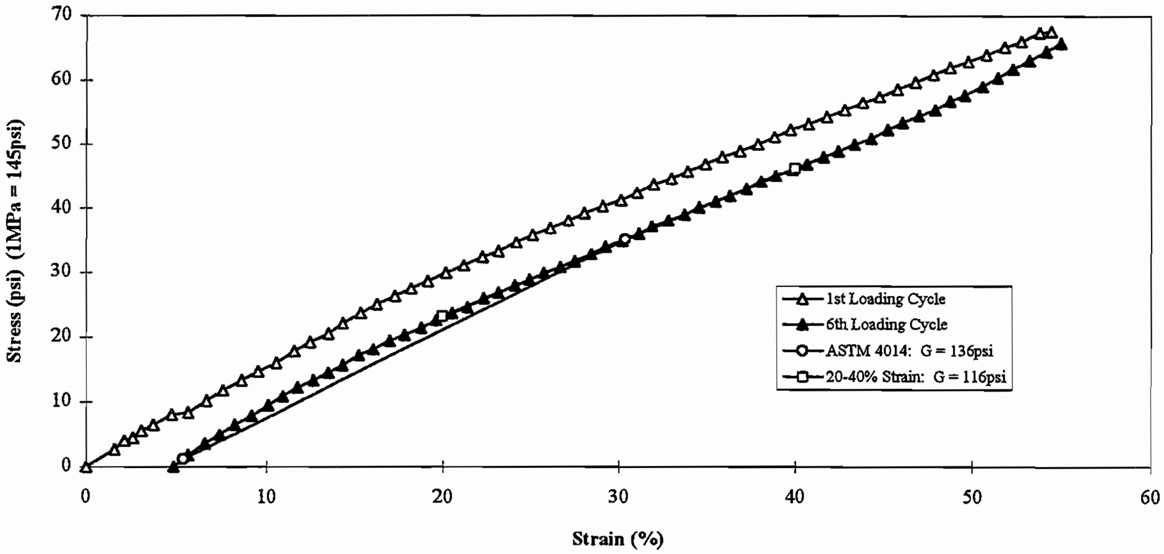


Figure 5- 2 *Stress-strain curves for one NR block from the 1S4_01, 02, 03, 04 specimens.*

Table 5- 1 *Summary of the calculated shear modulus values from all tests*

Specimen	Size	Gn	Method	Measured G	Measured G	Measured G
1S4_01	4" x 4" x 1"	100psi	ASTM D4014	136 psi	140 psi	142 psi
1S4_02			20-40% Strain	116 psi	118 psi	124 psi
1S4_03				σ =	σ =	σ =
1S4_04				0 psi	112 psi	146 psi
1S4_05	4" x 4" x 1"	100psi	ASTM D4014	142 psi	144 psi	148 psi
1S4_06			20-40% Strain	120 psi	121 psi	128 psi
1S4_07				σ =	σ =	σ =
1S4_08				0 psi	106 psi	150 psi
1S2_01	2" x 2" x 0.5"	100psi	ASTM D4014	148 psi	151 psi	155 psi
1S2_02			20-40% Strain	127 psi	129 psi	142 psi
1S2_03				σ =	σ =	σ =
1S2_04				0 psi	117 psi	233 psi
1S2_05	2" x 2" x 0.5"	100psi	ASTM D4014	148 psi	155 psi	157 psi
1S2_06			20-40% Strain	128 psi	133 psi	147 psi
1S2_07				σ =	σ =	σ =
1S2_08				0 psi	112 psi	238 psi
2S4_01	4" x 4" x 1"	200psi	ASTM D4014	195 psi	197 psi	200 psi
2S4_02			20-40% Strain	165 psi	169 psi	170 psi
2S4_03				σ =	σ =	σ =
2S4_04				0 psi	101 psi	146 psi
2S4_05	4" x 4" x 1"	200psi	ASTM D4014	188 psi	192 psi	200 psi
2S4_06			20-40% Strain	159 psi	164 psi	169 psi
2S4_07				σ =	σ =	σ =
2S4_08				0 psi	97 psi	133 psi
2S2_01	2" x 2" x 0.5"	200psi	ASTM D4014	209 psi	221 psi	239 psi
2S2_02			20-40% Strain	184 psi	189 psi	212 psi
2S2_03				σ =	σ =	σ =
2S2_04				0 psi	119 psi	213 psi
2S2_05	2" x 2" x 0.5"	200psi	ASTM D4014	211 psi	224 psi	232 psi
2S2_06			20-40% Strain	185 psi	191 psi	199 psi
2S2_07				σ =	σ =	σ =
2S2_08				0 psi	120 psi	240 psi

Note: 1MPa = 145 psi

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.

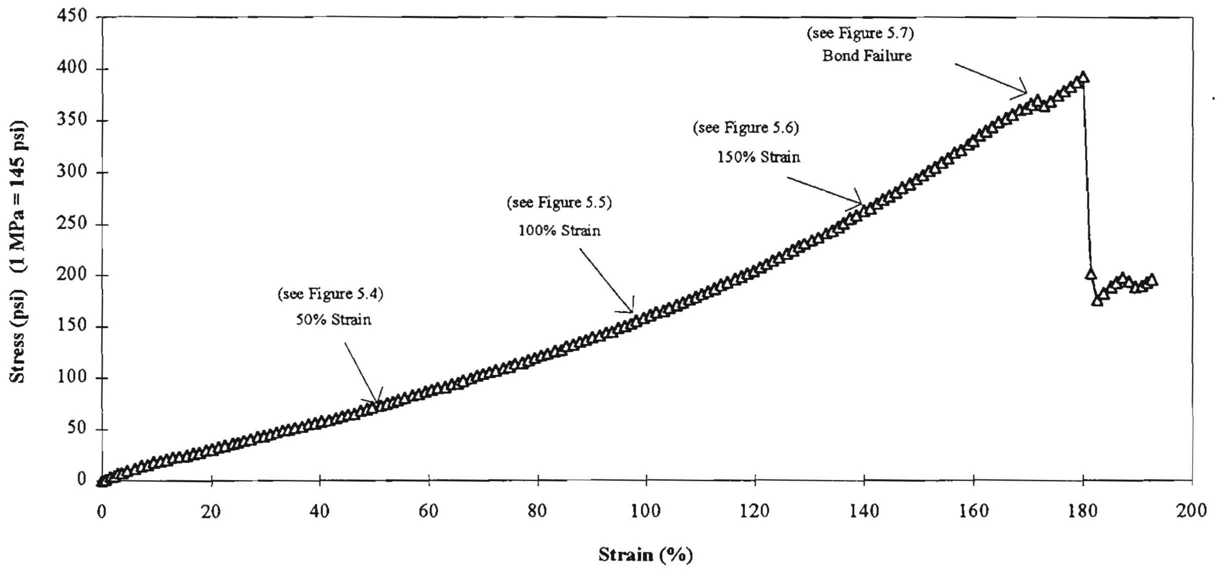


Figure 5- 3 *Shear stress-strain curve for one NR block from the 1S4_01, 02, 03, 04 specimen*

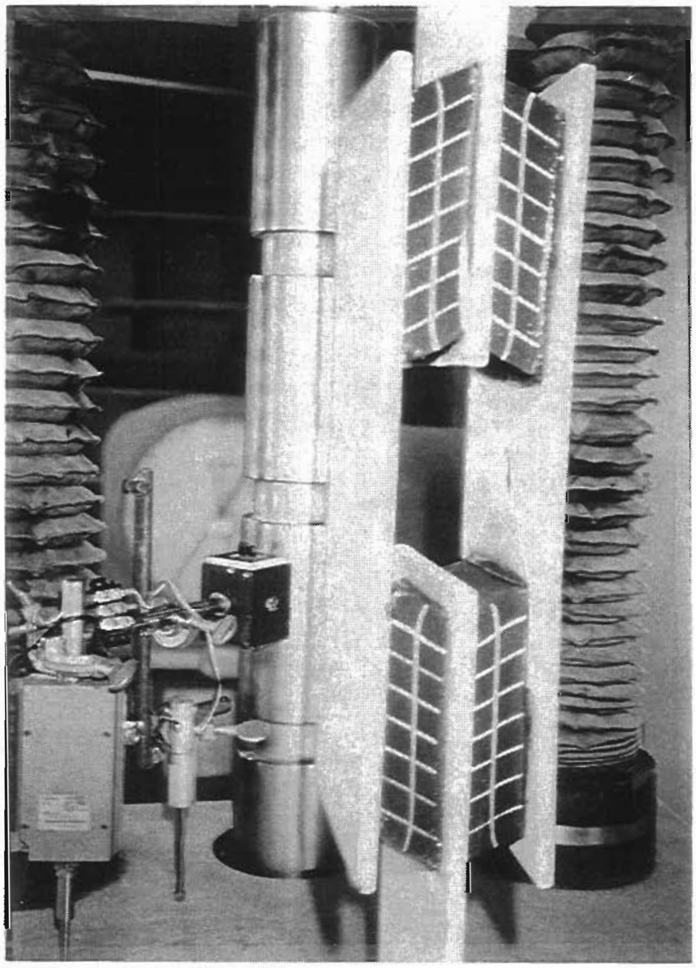


Figure 5- 4 Shear specimen at 50% strain

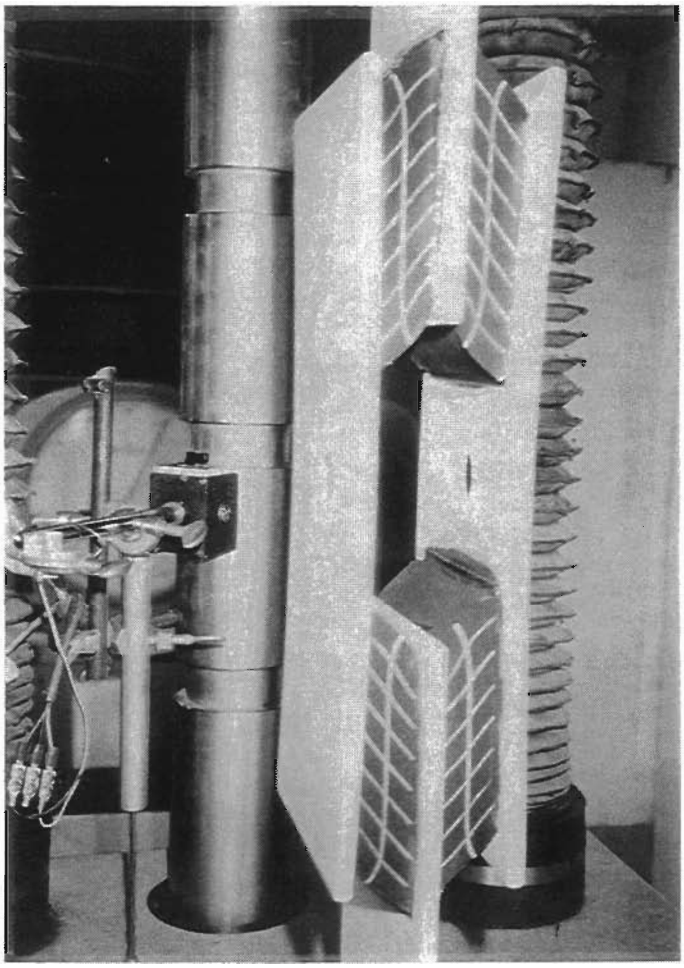


Figure 5- 5 Shear specimen at 100% strain

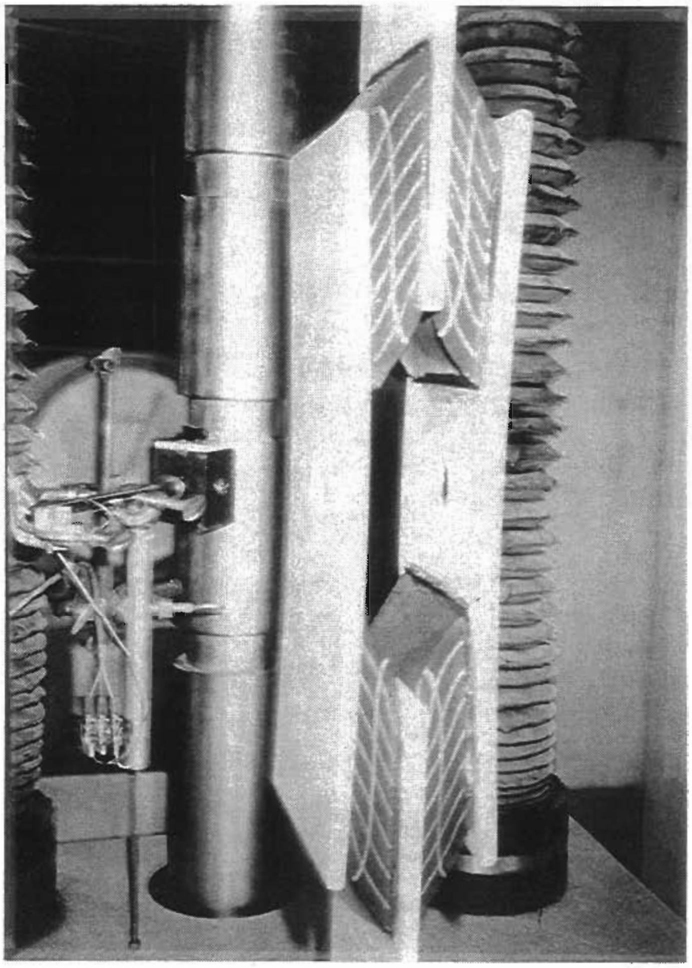


Figure 5- 6 Shear specimen at 150% strain

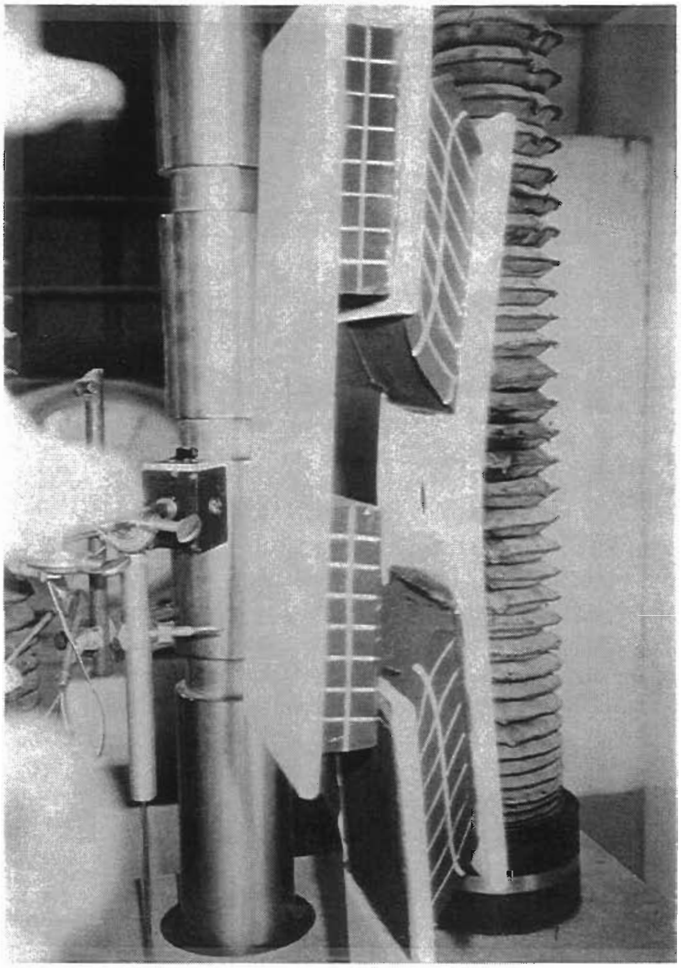


Figure 5- 7 Shear specimen showing bond failure

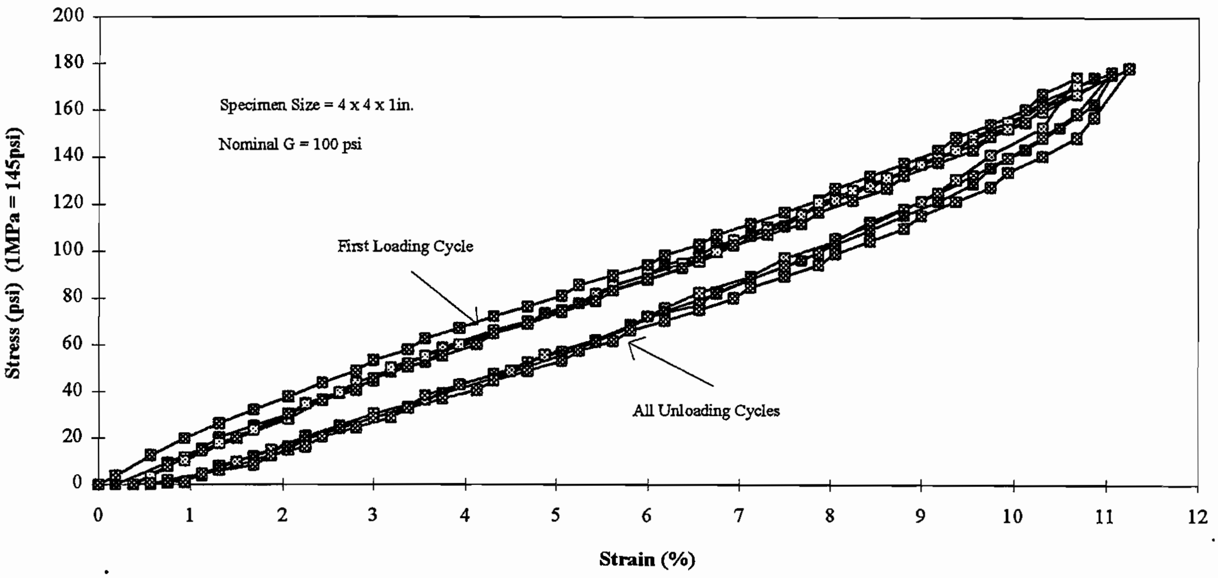


Figure 5- 8 Five loading-unloading cycles for the cmpression specimen 1C4_01

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.

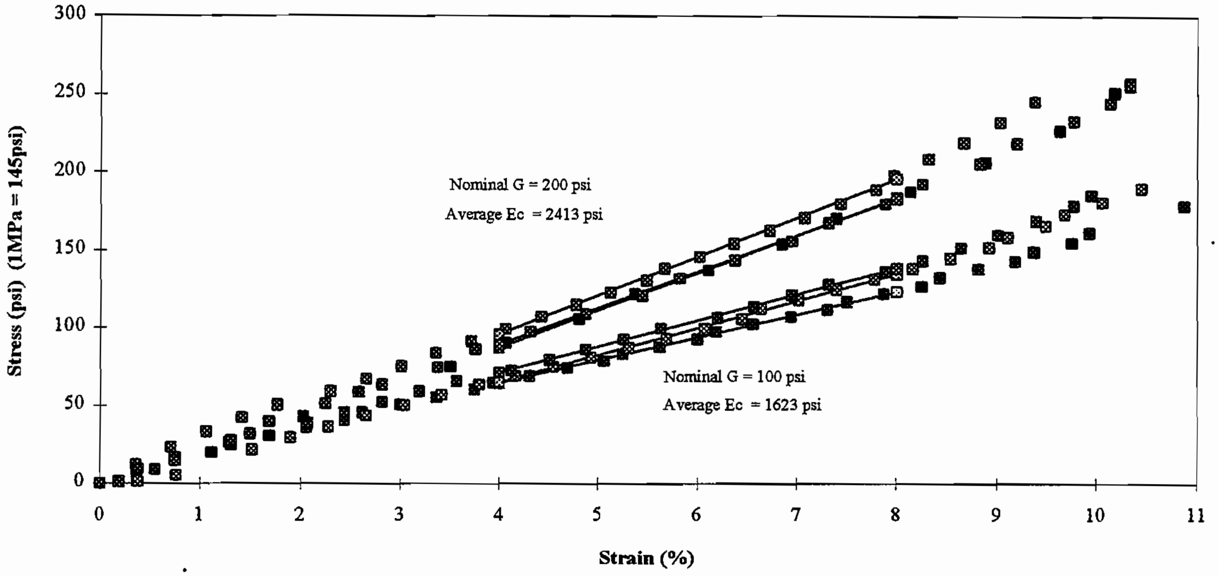


Figure 5- 9 *Compressive modulus values for the 4 x 4 x 1-in. specimens*

.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- 2 *Measured compressive modulus values for all specimens*

Nominal Shear Modulus	Size	Specimen #	Ec (psi)	Average Ec (psi)
100 psi	4" x 4" x 1"	1C4_01	1468	1623
100 psi	4" x 4" x 1"	1C4_02	1730	
100 psi	4" x 4" x 1"	1C4_03	1671	
100 psi	2" x 2" x 1/2"	1C2_01	1904	1920
100 psi	2" x 2" x 1/2"	1C2_02	1900	
100 psi	2" x 2" x 1/2"	1C2_03	1957	
200 psi	4" x 4" x 1"	2C4_01	2336	2413
200 psi	4" x 4" x 1"	2C4_02	2405	
200 psi	4" x 4" x 1"	2C4_03	2497	
200 psi	2" x 2" x 1/2"	2C2_01	2950	2634
200 psi	2" x 2" x 1/2"	2C2_02	2529	
200 psi	2" x 2" x 1/2"	2C2_03	2424	

Note : 145psi = 1MPa 1in. =

Table 5- 3 Comparison of the measured Ec values with the Ec values from Equation 3.2

Nominal G	Size	Specimen #	Measured Ec Average (psi)	Ec from Eq. 3.2 (G, ASTM 4014) (psi)	Ec from Eq. 3.2 (G, 20-40% Strain) (psi)
100 psi	4" x 4" x 1"	1C4_01	1623	2211	1809
100 psi	2" x 2" x 1/2"	1C2_01	1920	2273	1975
200 psi	4" x 4" x 1"	2C4_01	2413	3159	2675
200 psi	2" x 2" x 1/2"	2C2_01	2634	3613	3176

Note: 145psi = 1MPa 1in. = 25.4 mm

Table 5.4 summarizes the creep and stress relaxation values for all the compression specimens. It was noticed that the

Table 5- 4 Summary of the stress relaxation and creep values for all compression specimens

Specimen #	Max. Strain %	Final Strain %	Max. Stress (psi)	Stress After 5 minutes (psi)	Creep %	Stress Relaxation %
1C4_01	38.05	1.87	1511	1285	5	15
1C4_01	55.58	8.39	7435	6396	15	14
1C4_02	36.25	1.89	1474	1263	5	14
1C4_02	53.70	7.21	7276	6325	13	13
1C4_03	37.00	1.68	1440	1295	5	10
1C4_03	54.27	6.20	7173	6449	11	10
2C4_01	30.83	1.79	1505	1307	6	13
2C4_01	54.08	6.76	7480	6271	13	16
2C4_02	32.86	1.88	1496	1184	6	21
2C4_02	58.33	6.48	7616	6056	11	20
2C4_03	31.50	1.42	1538	1169	5	24
2C4_03	49.85	5.54	7373	5335	11	28
1C2_01	31.00	2.27	1047	913	7	13
1C2_01	47.26	5.29	5928	4138	11	30
1C2_02	31.58	2.81	1052	913	9	13
1C2_02	47.72	4.21	5958	4100	9	31
1C2_03	29.45	1.45	1063	914	5	14
1C2_03	47.64	4.36	5963	4100	9	31
2C2_01	24.53	1.51	1042	862	6	17
2C2_01	47.55	5.66	5910	4320	12	27
2C2_02	24.44	1.48	1065	859	6	19
2C2_02	43.70	4.81	5855	4689	11	20
2C2_03	23.33	1.11	936	761	5	19
2C2_03	45.56	5.93	5370	3717	13	31

Note: 145psi = 1MPa

% 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.

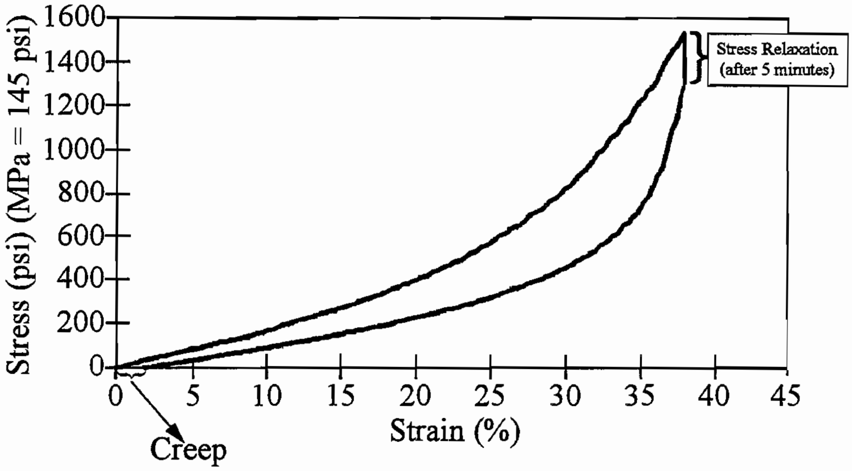


Figure 5- 10 *Compressive stress-strain curve for Specimen 1C4_01 showing stress relaxation and creep*

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.

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).

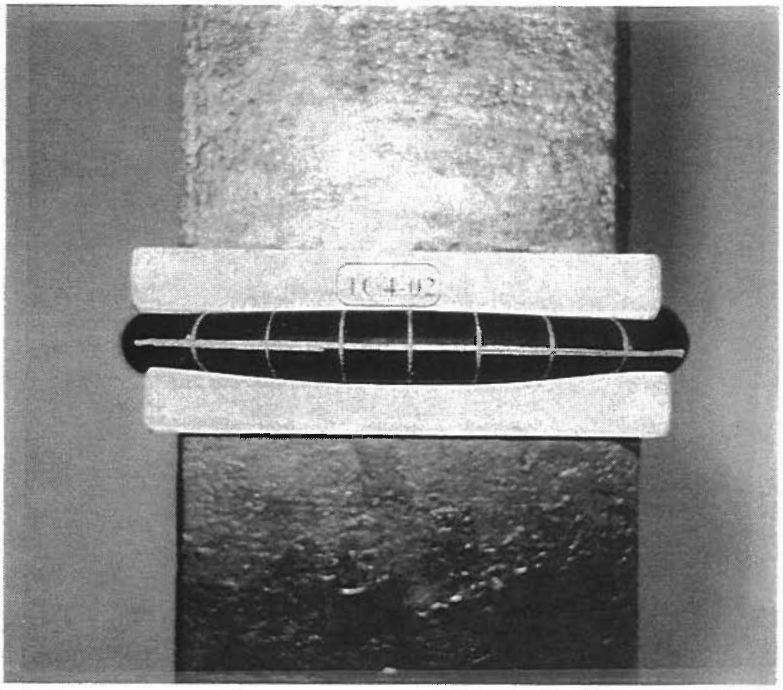


Figure 5- 11 Compressive specimen 1C4_02 at 55% strain

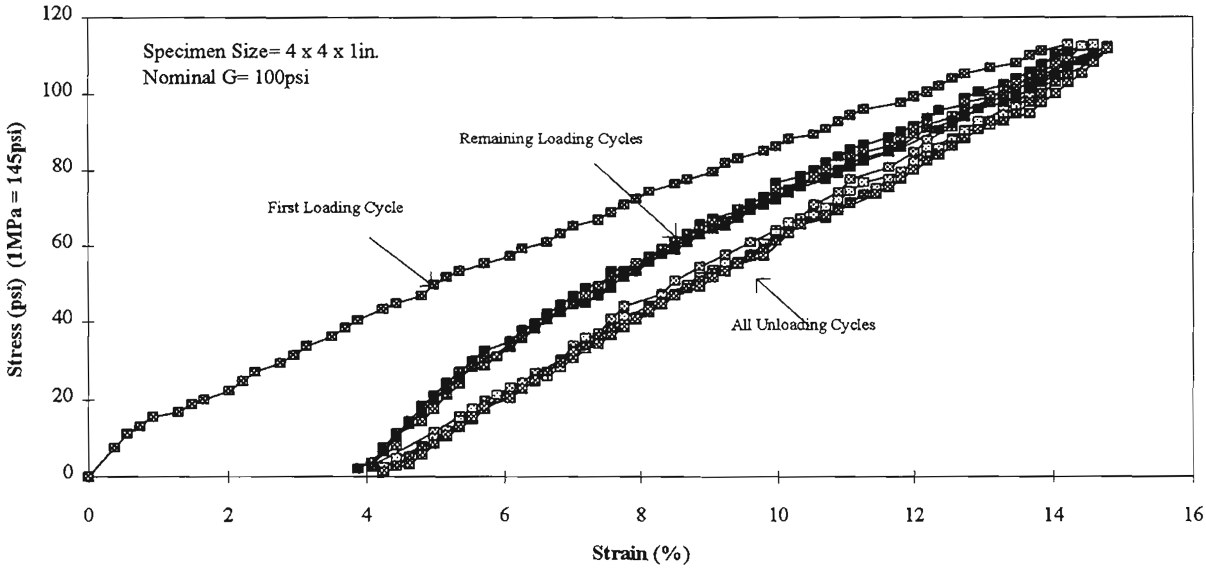


Figure 5- 12 Five loading-unloading cycles for the tension specimen 1T4_02

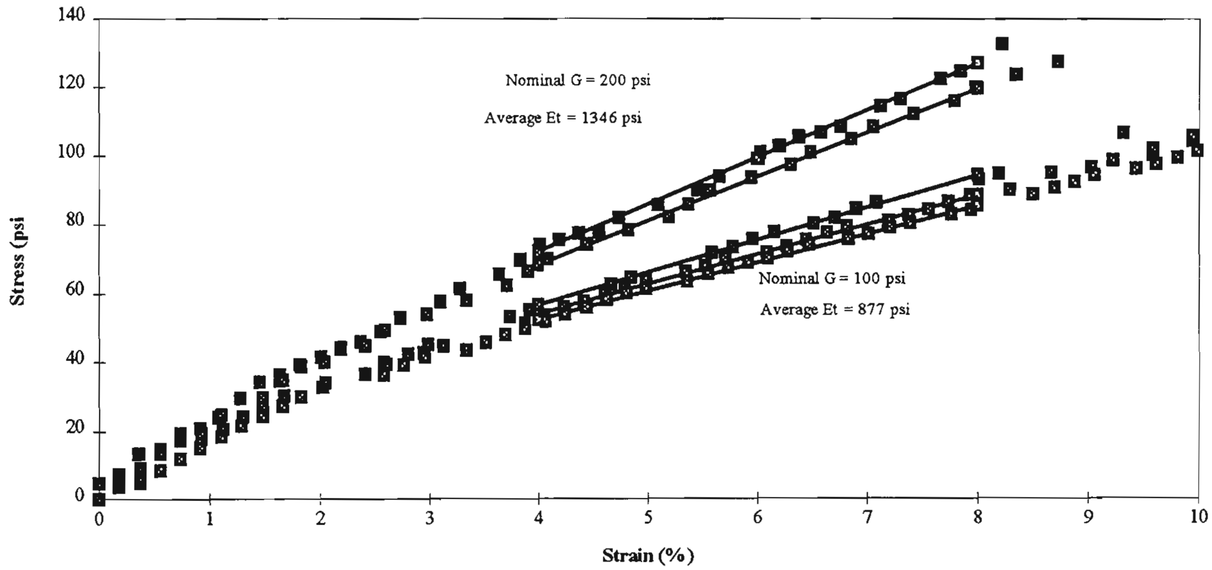


Figure 5- 13 *Tensile modulus values for the 4 x 4 x 1 in. specimens (1 in. = 25.4 mm)*

Table 5- 5 *Measured tensile modulus values for all specimen*

Nominal Shear Modulus	Size	Specimen #	Et (psi)	Average Et (psi)
100 psi	4" x 4" x 1"	1T4_01	861	
100 psi	4" x 4" x 1"	1T4_02	825	876
100 psi	4" x 4" x 1"	1T4_03	943	
100 psi	2" x 2" x 1/2"	1T2_01	1183	
100 psi	2" x 2" x 1/2"	1T2_02	971	1049
100 psi	2" x 2" x 1/2"	1T2_03	991	
200 psi	4" x 4" x 1"	2T4_01	1373	
200 psi	4" x 4" x 1"	2T4_02	1380	1346
200 psi	4" x 4" x 1"	2T4_03	1285	
200 psi	2" x 2" x 1/2"	2T2_01	1388	
200 psi	2" x 2" x 1/2"	2T2_02	1299	1347
200 psi	2" x 2" x 1/2"	2T2_03	1353	

Note: 145psi = 1MPa 1in. =

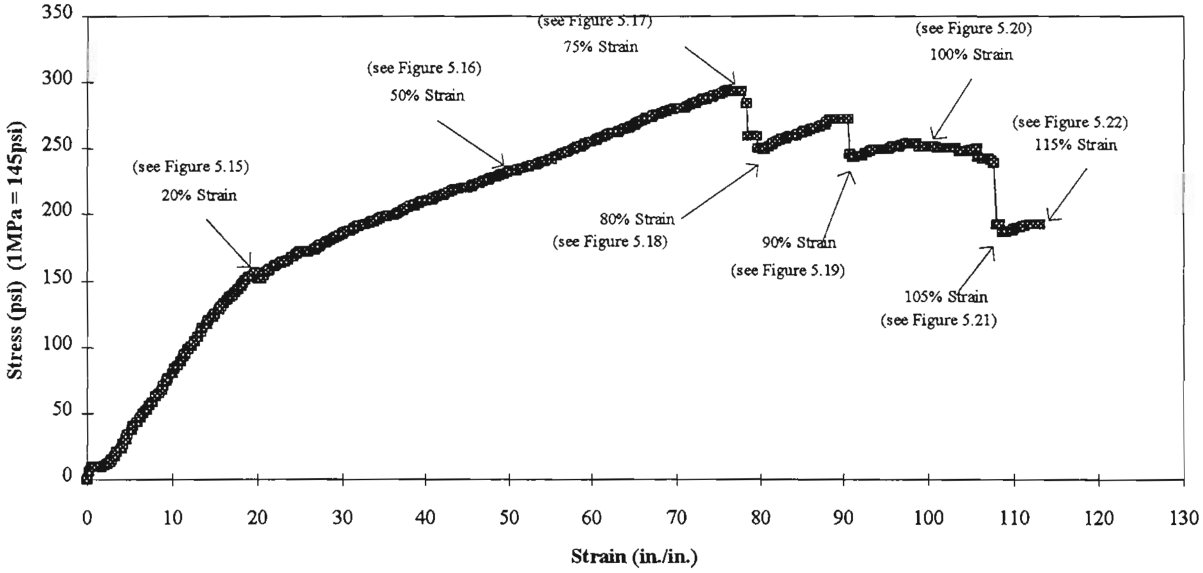


Figure 5- 14 Complete tensile stress-strain curve for Specimen 1T4_03

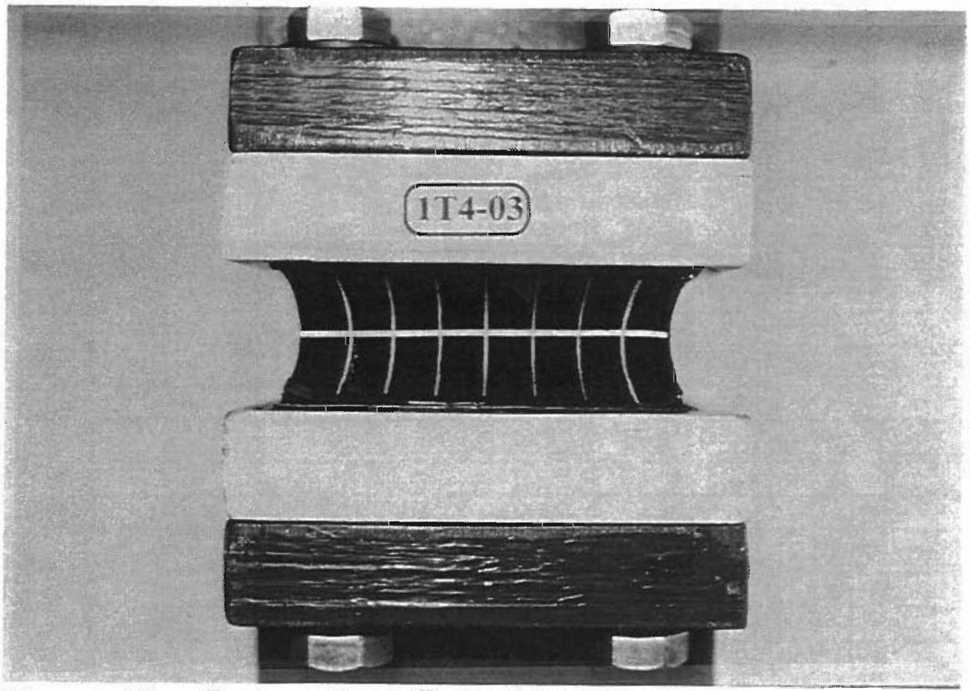


Figure 5- 15 Tension specimen 1T4_03 at 20% strains

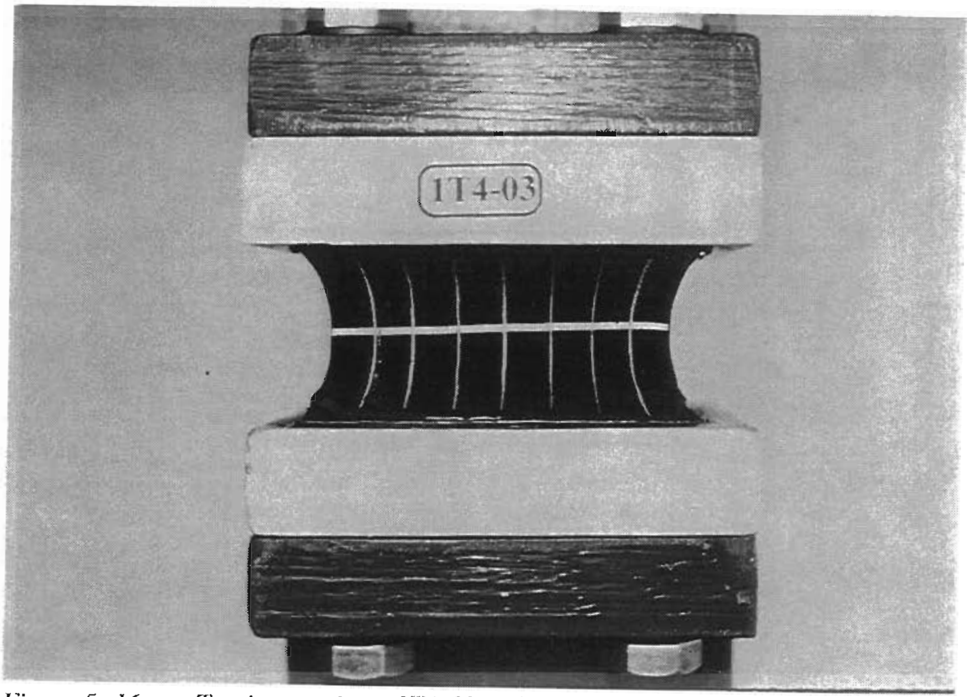


Figure 5- 16 Tension specimen 1T4_03 at 50% strains

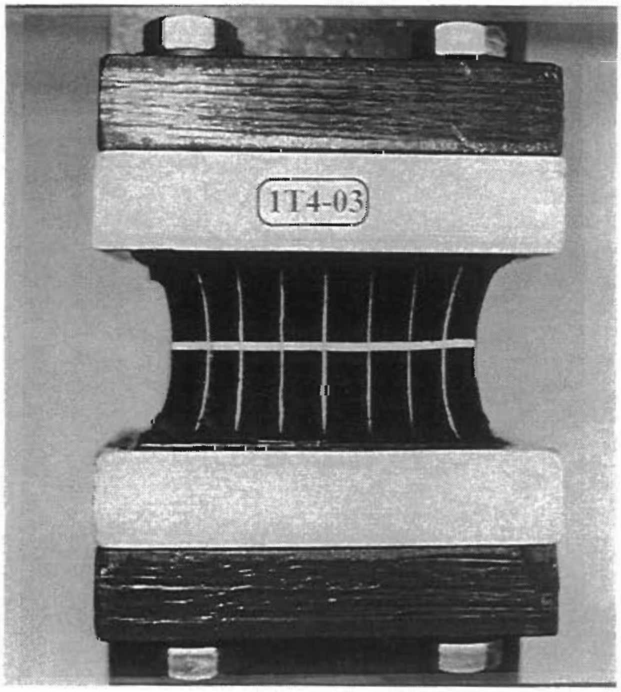


Figure 5- 17 Tension specimen 1T4_03 at 78% strains

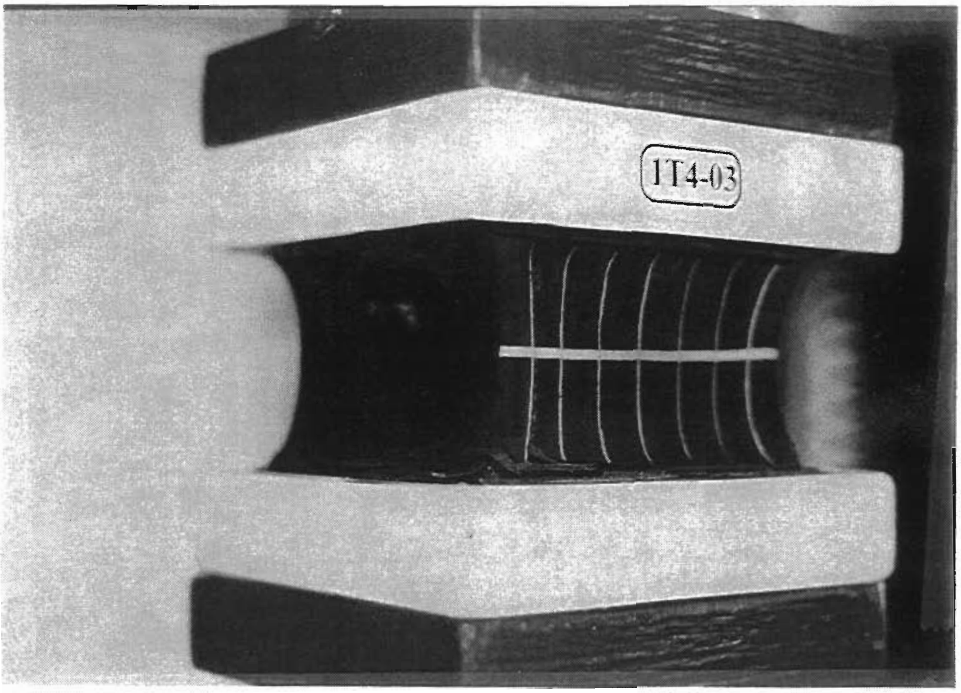


Figure 5- 18 Tension specimen 1T4_03 at initial rubber failure

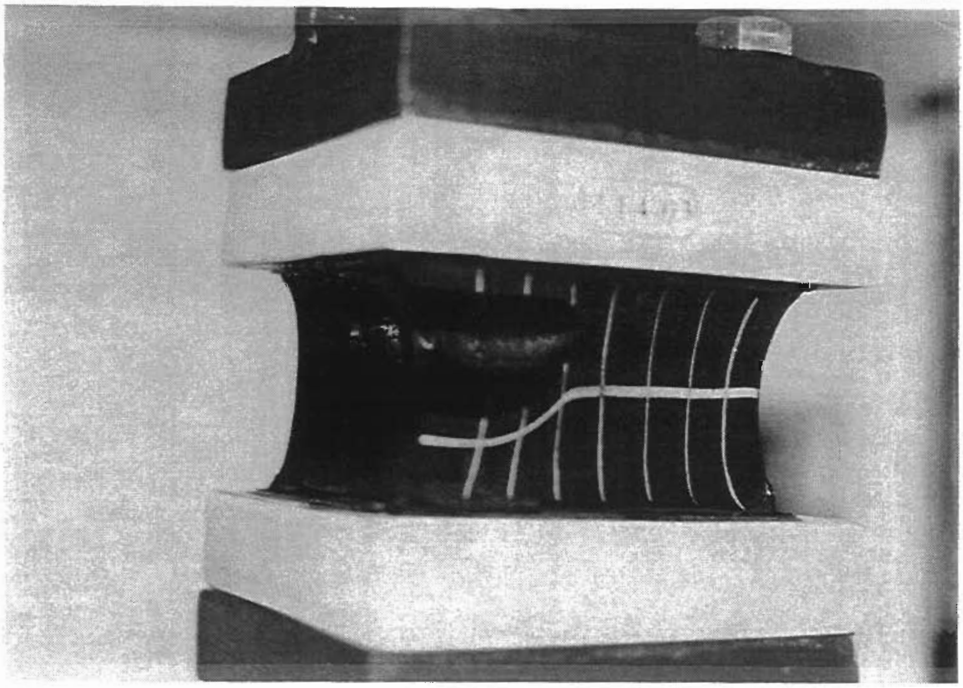


Figure 5- 19 Tension specimen 1T4_03 at 90% strain (tear propagation)

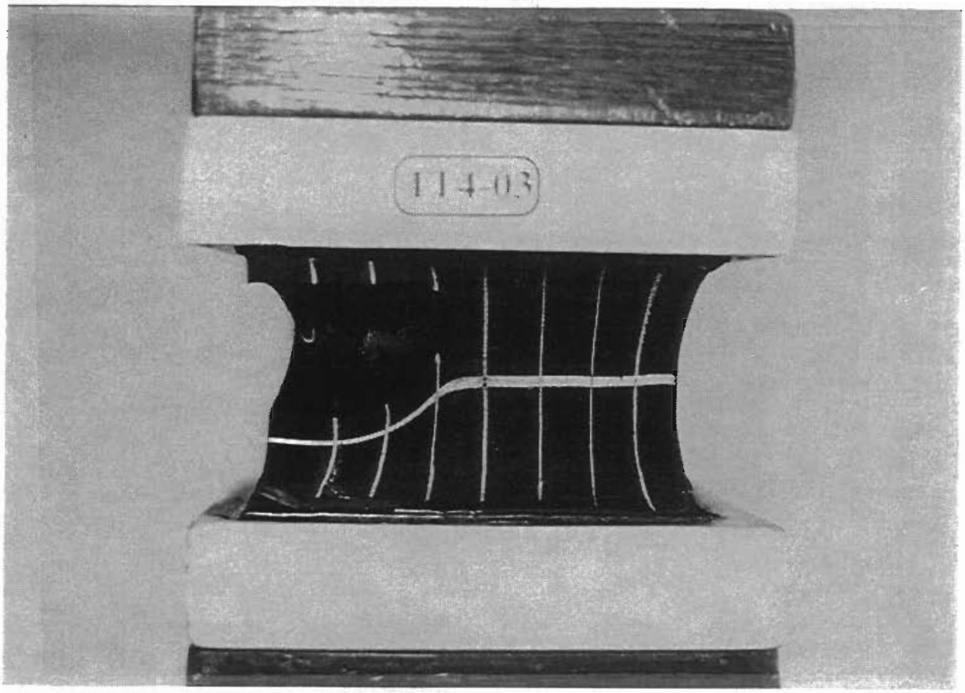


Figure 5- 20 Tension specimen 1T4_03 at 100% strain

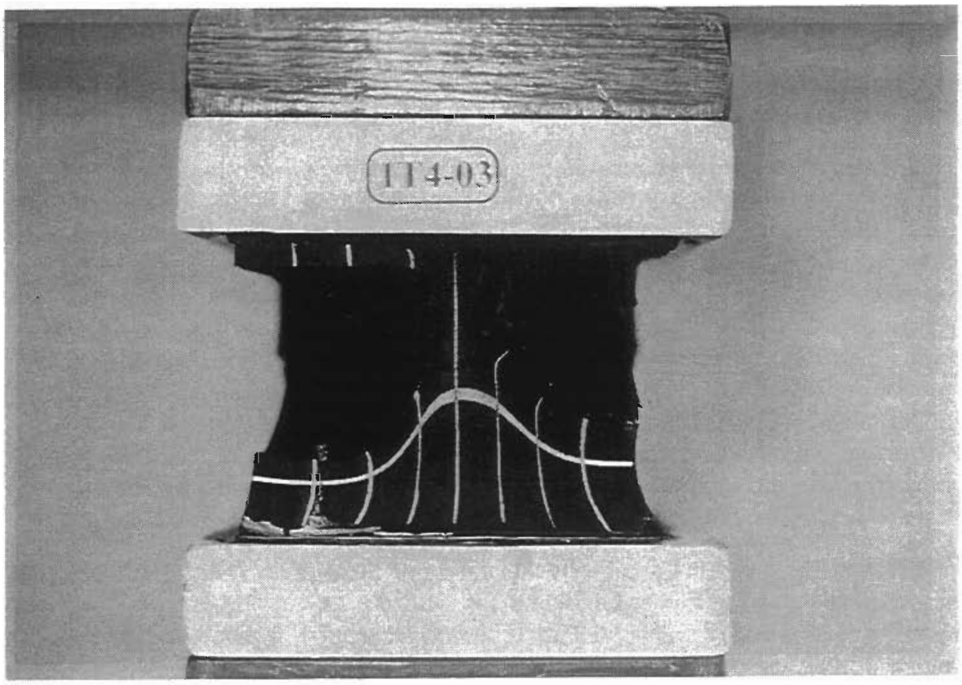


Figure 5- 21 Tension specimen 1T4_03 at 110% strains

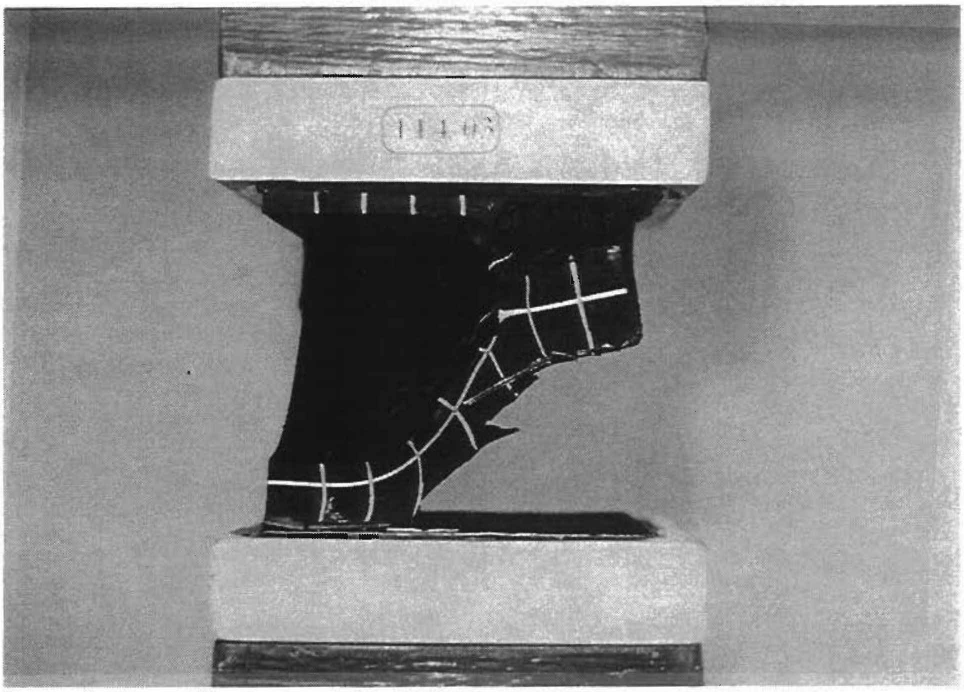


Figure 5- 22 Tension specimen 1T4_03 at 115% strains

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.

Table 5- 6 Average measured Ec, Et and G values and their interrelationship

Gn (psi)	Size (in)	Ec (psi)	Et (psi)	G (psi)	G/Gn	Ec/Et	Ec/G	Ec/G Average	Et/G	Et/G Average
100	4 x 4 x 1	1623	876	118	1.18	1.85	13.75		7.42	
100	2 x 2 x 1/2	1920	1049	128	1.28	1.83	15.00	14.38	8.20	7.81
200	4 x 4 x 1	2413	1346	162	0.81	1.79	14.90		8.31	
200	2 x 2 x 1/2	2634	1347	185	0.93	1.96	14.24	14.57	7.28	7.79

The combined compression and shear tests gave shear modulus values that wer 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.

The measured shear modulus values, based on the ASTM D4014 Annex A method and the linear relationship between 30% and 40% strain, of the 4 x 4 x 1 in. (101.6 x 101.6 x 25.4 mm) and the 2 x 2 x 0.5 in. (50.8 50.8 x 12.7 mm) specimens with G_n = 100 psi (0.69 MPa) and G_n = 200 psi (1.39 MPa) were compared with full-scale specimens which measured 9 x 14 x 2 in. (229 x 356 x 51 mm) with a total elastomer thickness of 1.75 in. (44.5 mm) and two 0.125 in. (3.2 mm) steel plates. The full scale specimens were tested in accordance with the procedures described by Muscarella (38). Table 5.7 presents this comparison with the shear modulus values of the small specimens determined using the 20-40% strain relationship and Table 5.8 presents this comparison with the shear modulus values of the small specimens determined utilizing the method described in Annex A of ASTM D4014.

Table 5- 7 Comparison of ASTM (20-40% strain) and full-scale shear modulus tests

Manufacturer	Nominal Shear Modulus psi (MPa)	Shear Modulus psi (MPa)		
		2 x 2 x 0.5in. (50.8 x 50.8 x 12.7mm)	4 x 4 x 1in. (101.6 x 101.6 x 25.4mm)	9 x 14 x 2in. (229 x 356 x 51mm)
A	100 (0.69)	127.5 (0.89)*	118 (0.825)*	98.6 (0.68)**
	200 (1.38)	184.5 (1.29)*	162 (1.13)*	122 (0.84)**

* Average values of two tests. Maximum deviation is +/- 2%.
** Average values of two tests. Maximum deviation is +/- 3.5%.

Table 5- 8 Comparison of ASTM (Annex A) and full-scale shear modulus tests

Manufacturer	Nominal Shear Modulus psi (MPa)	Shear Modulus psi (MPa)		
		2 x 2 x 0.5in. (50.8 x 50.8 x 12.7mm)	4 x 4 x 1in. (101.6 x 101.6 x 25.4mm)	9 x 14 x 2in. (229 x 356 x 51mm)
A	100 (0.69)	148 (1.02)*	139 (0.96)*	98.6 (0.68)**
	200 (1.38)	210 (1.45)*	191.5 (1.32)*	122 (0.84)**

* Average values of two tests. Maximum deviation is +/- 2%.
** Average values of two tests. Maximum deviation is +/- 3.5%.

These results indicate that the physical size and shape factor of the specimen may affect the measured shear modulus. From Table 5.7, the average shear modulus values for the 2in. (50.8mm) specimens are 11% (+/- 3%) higher than the 4in. (101.6mm) specimens and 40% (+/-11%) higher than the full scale specimens. From Table 5.8, the average values for the 2in. (50.8mm) specimens are 8% (+/- 3%) higher than the 4in. (101.6mm) specimens and 61% (+/- 11%) higher than the full scale specimens. Shape factor (SF) may also contribute to the large differences in measured shear modulus values between the small specimens which have a SF of 1 and the full scale specimens which have a shape factor of 4.7 (38), but it does not account for the differences between the 2in. (50.8mm) and 4in. (101.6mm) specimens.

The significant difference between the measured shear modulus of the full scale specimens versus the ASTM specimens, however, may also indicate that the method of testing specimens influences the measured shear modulus. The ASTM test specimens were sheared to 50% strain in one direction while the full scale specimens were tested by cycling the bearings through strains of +/- 50%. It is possible that straining the bearings in two directions reduces the material stiffness more than straining in one direction, and thus a lower shear modulus is obtained. Another important difference is the ASTM specimens are epoxied to steel plates to hold them in position for the test and the full scale specimens are held in place by a compression force.

A theoretical study performed by Hamzeh (39) has shown that unbonded pads curl up at the ends when they are sheared which results in a corresponding reduction in shear modulus. He found that the shear modulus of a friction-held pad is a function of the number of steel shims and the thickness of the pad, and developed an empirical factor, α, to correct for these differences:

$\alpha = 1.0$ for a bonded pad
$\alpha = 0.95$ for a 6-shim pad
$\alpha = 0.8$ to 0.9 for a 3-shim pad

Measured shear modulus values are lower as the number of steel shims in the bearings decreases. The full scale results reported in Table 5.7 (bearings with two steel shims) are scaled by 1/ 0.8 which is the lower bound of a three-shim pad, and compared with the shear modulus values for the 4 x 4 x 1in. (101.6 x 101.6 x 25.4mm) specimens. The results, presented in Table 5.9, demonstrate that based on the 20 - 40% strain values, the small specimens were 4.3% less than the full scale value for G_n = 100psi (0.69MPa) and 6.3% greater for G_n = 200psi (1.38MPa). Based on the Annex A values, the small specimens were 12.7% and 25.6% greater than the full scale specimens for G_n = 100psi (0.69MPa) and G_n = 200psi (1.38MPa), respectively.

Table 5- 9 Comparison of ASTM and 20 - 40% Strain versus Full Scale (Adjusted) Tests

Manufacturer	G_n psi (MPa)	Shear Modulus psi (MPa)		
		ASTM Annex A	20 - 40% Strain	Full Scale/α
		4 x 4 x 1in. (101.6 x 101.6 x 25.4mm)	4 x 4 x 1in. (101.6 x 101.6 x 25.4mm)	9 x 14 x 2in. (229 x 356 x 51mm)
A	100 (0.69)	139 (0.96)	118 (0.825)	123.3 (0.85)
	200 (1.38)	191.5 (1.32)	162 (1.13)	152.5 (1.05)

While Table 5.9 indicates a possible correlation between the shear modulus values obtained from full scale tests and the 20 - 40% strain relationship from the ASTM tests, the sample size is small. Further tests are required to investigate the effect of specimen size and the influence of test method on the measured shear modulus.

CHAPTER 6

ADDITIONAL TESTS ON NATURAL RUBBER SPECIMENS

6.1 Scope

One year after the initial tests were performed, additional ASTM D4014 - 89 tests were conducted. The purpose of these tests was to verify the results of the shear modulus tests conducted one year earlier, to increase the sample size to include other manufacturers' products and to vary the shape factor (SF) in order to examine its influence on the measured shear modulus. To determine the influence of the test method, additional full scale tests were conducted according to the procedures described by Muscarella (38). The procedure for the full scale specimens was modified by straining the bearings in one direction only which followed the ASTM test method. Comparisons are made between the shear modulus values obtained from the different types of test in order to ascertain any correlations between the quad shear tests and the full scale test.

6.2 1995 ASTM Tests

The elastomer material for the additional ASTM tests was provided by three different manufacturers identified in this report as A, B and C. All bearing pads were ordered by requesting G_n of 100psi (0.69MPa) and 200psi (1.38MPa). Plain pads measuring 9 x 28 x 1in. (229 x 711 x 25.4mm) were cut to provide specimens for the tests. In order to replicate the initial tests, 4 x 4 x 1in. (101.6 x 101.6 x 25.4mm) specimens with SF of 1 were prepared according to the procedures described in Chapter 4. Specimens measuring 2 x 2 x 1in. (50.8 x 50.8 x 25.4mm) with SF of 0.5 were also prepared in the same manner. Because of material constraints, 6 x 6 x 1in. (152.4 x 152.4 x 25.4mm) specimens with SF of 1.5 could only be produced for manufacturer A. Each test specimen was prepared and tested with strict adherence to the procedures described in Chapter 4.

The physical properties of each specimen were measured according to the Section 4.5 procedures and these values are presented in Tables 6.1a, 6.1b and 6.1c. The measured properties were length, width, thickness, and hardness. From these measurements, the area and the shape factor of each specimen was calculated. The specimens were numbered in such a way to indicate G_n, manufacturer, dimension and quantity of specimens that fell under the same category. For example, the first character represents G_n: 1 refers to 100psi (0.69MPa) and 2 refers to 200psi (1.38MPa). The second character refers to manufacturer A, B or C. The third character is the length or width dimension and the last character is the number of specimens that fell under the same category of the first three characters.

The results of the quad shear tests are in Tables 6.2a, 6.2b and 6.2c. Shear modulus values were calculated utilizing the Annex A formula and the linear relationship between 20 - 40% strain. There is very little scatter among similar specimens (same manufacturer and same size) and the maximum deviation of any two set of values is +/- 2.5%.

Table 6.3 summarizes the average shear modulus values for Manufacturers A, B and C, based on ASTM Annex A formula and the 20 - 40% strain relationship.

The 20 - 40% strain method always gave a lower shear modulus than the ASTM Annex A method. The average difference between these two methods for all the data in Table 6.3 is 17.6% (+/- 5%). Table 6.3 also illustrates the differences in shape factor. The results indicate that for Manufacturer A, based on the ASTM Annex A method, the shear modulus tends to increase as the SF increases. The same results from manufacturers B and C seem to indicate the opposite: The shear modulus decreases as the SF increases.

The results also indicate that based on the 20 - 40% strain criteria, shape factor does not seem to influence the measured shear modulus. Table 6.4 presents the results from the 2in. (50.8mm) and the 4in. (101.6mm)

Table 6- 1a Physical properties of the shear specimens - Manufacturer A

Specimen Number	G_n (psi)	Hardness (Shore A)	Average Length (in.)	Average Width (in.)	Average Thickness (in.)	Area (in.^{2})	Shape Factor
1A4-5	100	66.0	3.996	3.973	1.068	15.875	0.933
1A4-6	100	65.0	3.990	4.022	1.096	16.046	0.913
1A4-7	100	66.0	3.995	4.011	1.092	16.026	0.917
1A4-8	100	66.0	4.044	4.012	1.095	16.224	0.920
2A4-1	200	70.0	3.937	3.966	1.087	15.613	0.909
2A4-2	200	73.0	3.970	4.037	1.071	16.023	0.935
2A4-3	200	70.0	4.003	3.973	1.097	15.901	0.909
2A4-4	200	72.5	3.963	3.945	1.090	15.632	0.907
2A4-5	200	70.5	3.939	3.945	1.075	15.540	0.917
2A4-6	200	72.5	4.039	4.010	1.090	16.198	0.923
2A4-7	200	72.0	3.977	4.004	1.070	15.925	0.932
2A4-8	200	70.0	3.969	4.028	1.076	15.985	0.929
1A2-1	100	65.5	2.043	1.957	1.089	3.996	0.459
1A2-2	100	64.0	1.976	1.983	1.080	3.918	0.458
1A2-3	100	66.5	2.010	1.962	1.094	3.944	0.454
1A2-4	100	65.0	1.978	1.950	1.084	3.857	0.453
1A2-5	100	65.0	2.007	2.000	1.085	4.012	0.462
1A2-6	100	63.5	1.999	2.053	1.090	4.105	0.465
1A2-7	100	65.0	2.021	2.054	1.099	4.150	0.464
1A2-8	100	63.5	2.033	2.048	1.092	4.162	0.467
2A2-1	200	72.5	1.957	2.005	1.090	3.924	0.454
2A2-2	200	70.5	1.986	2.031	1.085	4.034	0.463
2A2-3	200	73.5	2.032	1.995	1.097	4.055	0.459
2A2-4	200	73.5	2.027	1.937	1.091	3.924	0.454
2A2-5	200	74.0	1.974	1.940	1.088	3.829	0.450
2A2-6	200	70.5	2.070	2.034	1.083	4.211	0.474
2A2-7	200	71.0	2.022	1.981	1.093	4.005	0.458
2A2-8	200	70.0	1.990	1.975	1.093	3.929	0.453
1A6-1	100	65.5	6.049	5.953	1.097	36.008	1.368
1A6-2	100	66.5	6.069	6.015	1.096	36.504	1.378
1A6-3	100	63.5	6.118	6.003	1.074	36.723	1.411
1A6-4	100	63.0	6.075	6.010	1.092	36.511	1.383
2A6-1	200	71.0	6.002	5.972	1.095	35.842	1.367
2A6-2	200	70.5	5.990	6.013	1.087	36.016	1.380
2A6-3	200	71.0	5.980	6.017	1.089	35.983	1.377
2A6-4	200	70.0	6.049	5.991	1.095	36.241	1.375

Table 6- 1b *Physical properties of the shear specimens - Manufacturer B*

Specimen Number	G_n (psi)	Hardness (Shore A)	Average Length (in.)	Average Width (in.)	Average Thickness (in.)	Area (in.^{2})	Shape Factor
1B4-1	100	56.0	4.030	4.037	1.045	16.271	0.965
1B4-2	100	58.0	4.021	4.000	1.047	16.081	0.958
1B4-3	100	57.0	4.009	3.963	1.038	15.887	0.960
1B4-4	100	56.5	3.961	3.967	1.033	15.712	0.959
1B4-5	100	55.5	4.033	3.980	1.034	16.048	0.969
1B4-6	100	55.5	4.079	3.997	1.038	16.303	0.972
1B4-7	100	56.5	4.044	3.985	1.031	16.114	0.974
1B4-8	100	58.0	3.961	3.954	1.037	15.661	0.955
2B4-1	200	67.5	4.041	4.029	1.053	16.281	0.958
2B4-2	200	68.0	4.016	4.040	1.069	16.222	0.942
2B4-3	200	68.0	3.980	4.021	1.049	16.003	0.954
2B4-4	200	69.5	3.996	4.050	1.077	16.181	0.934
2B4-5	200	68.0	3.966	3.929	1.066	15.584	0.926
2B4-6	200	69.0	4.036	3.931	1.069	15.864	0.932
2B4-7	200	68.0	4.029	4.000	1.082	16.115	0.928
2B4-8	200	68.5	4.011	3.994	1.082	16.019	0.925
1B2-1	100	56.5	1.992	1.995	1.033	3.975	0.483
1B2-2	100	56.0	1.958	1.998	1.043	3.912	0.474
1B2-3	100	57.5	2.006	1.975	1.045	3.962	0.476
1B2-4	100	58.0	1.989	1.995	1.046	3.968	0.476
1B2-5	100	56.5	2.030	1.945	1.037	3.947	0.479
1B2-6	100	58.5	1.960	1.961	1.045	3.844	0.469
1B2-7	100	58.5	2.023	2.003	1.047	4.051	0.480
1B2-8	100	56.5	1.944	1.946	1.044	3.782	0.466
2B2-1	200	69.0	2.002	1.983	1.064	3.970	0.468
2B2-2	200	69.0	2.007	1.975	1.067	3.962	0.466
2B2-3	200	68.5	1.994	1.998	1.058	3.984	0.472
2B2-4	200	69.0	1.998	2.011	1.069	4.017	0.469
2B2-5	200	69.5	1.999	2.006	1.080	4.010	0.464
2B2-6	200	69.0	2.021	1.994	1.077	4.029	0.466
2B2-7	200	68.5	1.973	2.023	1.074	3.991	0.465
2B2-8	200	69.5	2.007	1.996	1.073	4.005	0.466

Table 6- 1c *Physical properties of shear specimens - Manufacturer C*

Specimen Number	G_n (psi)	Hardness (Shore A)	Average Length (in.)	Average Width (in.)	Average Thickness (in.)	Area (in.^{2})	Shape Factor
1C4-1	100	53.5	3.966	3.954	0.957	15.682	1.035
1C4-2	100	54.0	3.985	4.027	0.975	16.047	1.027
1C4-3	100	54.0	4.039	3.989	0.951	16.109	1.055
1C4-4	100	55.0	3.999	3.963	0.951	15.849	1.047
1C4-5	100	54.0	4.009	3.959	0.956	15.868	1.042
1C4-6	100	53.0	4.010	4.037	0.950	16.185	1.059
1C4-7	100	53.5	4.027	4.002	0.952	16.115	1.054
1C4-8	100	55.0	4.014	3.985	0.971	15.995	1.030
2C4-1	200	70.0	3.949	4.011	0.993	15.836	1.002
2C4-2	200	70.5	3.992	3.966	0.977	15.828	1.018
2C4-3	200	68.5	4.008	4.006	1.005	16.056	0.997
2C4-4	200	69.5	4.007	3.998	0.990	16.021	1.011
2C4-5	200	68.5	3.962	3.968	0.979	15.722	1.012
2C4-6	200	68.5	4.011	3.984	0.989	15.980	1.011
2C4-7	200	69.5	3.971	3.978	0.975	15.794	1.019
2C4-8	200	67.0	3.979	4.002	0.998	15.922	1.000
1C2-1	100	54.0	2.052	1.978	0.952	4.059	0.529
1C2-2	100	54.0	2.036	1.980	0.955	4.032	0.526
1C2-3	100	53.0	1.919	1.972	0.958	3.784	0.507
1C2-4	100	54.0	1.949	1.968	0.959	3.835	0.511
1C2-5	100	54.5	1.999	2.059	0.955	4.115	0.531
1C2-6	100	53.5	1.988	1.966	0.955	3.909	0.518
1C2-7	100	54.5	1.964	2.024	0.955	3.973	0.522
1C2-8	100	53.0	2.005	1.936	0.961	3.882	0.513
2C2-1	200	69.5	2.036	2.023	0.989	4.119	0.513
2C2-2	200	69.5	2.037	1.981	0.990	4.035	0.507
2C2-3	200	70.0	2.032	2.015	0.974	4.093	0.519
2C2-4	200	70.0	2.011	2.015	0.989	4.050	0.509
2C2-5	200	70.0	2.011	2.002	0.974	4.026	0.515
2C2-6	200	70.5	2.026	1.962	0.980	3.974	0.508
2C2-7	200	70.0	2.009	1.991	0.992	4.000	0.504
2C2-8	200	69.5	1.992	2.011	0.981	4.006	0.510

Table 6- 2a   Summary of the calculated shear modulus - Manufacturer A

Specimen	Quad Shear Test Number	Nominal G (psi)	Measured G (psi) (ASTM Annex A)	Measured G(psi) (20 - 40% Strain)
1A4-5	ST1A4-2	100	152.3	122.1
1A4-6				
1A4-7				
1A4-8				
2A4-1	ST2A4-1	200	213.5	174.1
2A4-2				
2A4-3				
2A4-4				
2A4-5	ST2A4-2	200	224.3	182.9
2A4-6				
2A4-7				
2A4-8				
1A2-1	ST1A2-1	100	149.5	123.6
1A2-2				
1A2-3				
1A2-4				
1A2-5	ST1A2-2	100	148	120.6
1A2-6				
1A2-7				
1A2-8				
2A2-1	ST2A2-1	200	214.8	180.4
2A2-2				
2A2-3				
2A2-4				
2A2-5	ST2A2-2	200	209.5	177.3
2A2-6				
2A2-7				
2A2-8				
1A6-1	ST1A6-1	100	163.7	134.7
1A6-2				
1A6-3				
1A6-4				
2A6-1	ST2A6-1	200	212.5	187.3
2A6-2				
2A6-3				
2A6-4				

Table 6- 2b Summary of the calculated shear modulus - Manufacturer B

Specimen Number	Quad Shear Test Number	Nominal G (psi)	Measured G (psi) (ASTM Annex A)	Measured G(psi) (20 - 40% Strain)
1B4-1	ST1B4-1	100	115.5	86.3
1B4-2				
1B4-3				
1B4-4				
1B4-5	ST1B4-2	100	115.9	98.7
1B4-6				
1B4-7				
1B4-8				
2B4-1	ST2B4-1	200	183.8	148.9
2B4-2				
2B4-3				
2B4-4				
2B4-5	ST2B4-2	200	187	152.1
2B4-6				
2B4-7				
2B4-8				
1B2-1	ST1B2-1	100	129.7	100.3
1B2-2				
1B2-3				
1B2-4				
1B2-5	ST1B2-2	100	131.4	104.5
1B2-6				
1B2-7				
1B2-8				
2B2-1	ST2B2-1	200	190.3	154.1
2B2-2				
2B2-3				
2B2-4				
2B2-5	ST2B2-2	200	193.2	156.8
2B2-6				
2B2-7				
2B2-8				

Table 6- 2c Summary of the calculated shear modulus - Manufacturer C

Specimen Number	Quad Shear Test Number	Nominal G (psi)	Measured G (psi) (ASTM Annex A)	Measured G(psi) (20 - 40% Strain)
1C4-1 1C4-2 1C4-3 1C4-4	ST1C4-1	100	122	104.9
1C4-5 1C4-6 1C4-7 1C4-8	ST1C4-2	100	121.1	108.6
2C4-1 2C4-2 2C4-3 2C4-4	ST2C4-1	200	187.6	152.6
2C4-5 2C4-6 2C4-7 2C4-8	ST2C4-2	200	180.4	143.8
1C2-1 1C2-2 1C2-3 1C2-4	ST1C2-1	100	125.3	110.9
1C2-5 1C2-6 1C2-7 1C2-8	ST1C2-2	100	124.1	110.6
2C2-1 2C2-2 2C2-3 2C2-4	ST2C2-1	200	202.1	157.2
2C2-5 2C2-6 2C2-7 2C2-8	ST2C2-2	200	199	152.8

Table 6- 3 Summary of shear modulus values by shape factor - Manufacturers A, B, and C

Manufacturer	G_n psi (MPa)	Shear Modulus psi (MPa)					
		SF = 0.5		SF = 1.0		SF = 1.5	
		2 x 2 x 1in. (50.8 x 50.8 x 25.4mm)		4 x 4 x 1in. (101.6 x 101.6 x 25.4mm)		6 x 6 x 1in. (152.4 x 152.4 x 25.4mm)	
		ASTM Annex A	20-40% Strain	ASTM Annex A	20-40% Strain	ASTM Annex A	20-40% Strain
A	100 (0.69)	148.8 (1.03)	122.1 (0.84)	152.3 (1.05)	122.1 (0.84)	163.7 (1.13)	134.7 (0.93)
	200 (1.38)	212.2 (1.46)	178.9 (1.23)	218.9 (1.51)	178.5 (1.23)	212.5 (1.47)	187.3 (1.29)
B	100 (0.69)	130.6 (0.90)	102.4 (0.71)	115.7 (0.80)	92.5 (0.64)		
	200 (1.38)	191.8 (1.32)	155.5 (1.07)	185.4 (1.28)	150.5 (1.04)		
C	100 (0.69)	124.7 (0.86)	110.8 (0.76)	121.6 (0.84)	106.8 (0.74)		
	200 (1.38)	200.6 (1.38)	155.0 (1.07)	184.0 (1.27)	148.2 (1.02)		

Table 6- 4 Summary of shear modulus values by shape factor - Manufacturers A, B, and C

Manufacturer	Nominal Shear Modulus psi (MPa)	Shear Modulus psi (MPa)		Percent Difference from 4in. (101.6mm)
		SF = 0.5	SF = 1.0	
		2 x 2 x 1in. (50.8 x 50.8 x 25.4mm)	4 x 4 x 1in. (101.6 x 101.6 x 25.4mm)	
A	100 (0.69)	122.1 (0.84)	122.1 ((0.84)	0
	200 (1.38)	178.9 (1.23)	178.5 (1.23)	+ 0.2
B	100 (0.69)	102.4 (0.71)	92.5 (0.64)	+ 10.7
	200 (1.38)	155.5 (1.07)	150.5 (1.04)	+ 3.3
C	100 (0.69)	110.8 (0.76)	106.8 (0.74)	+ 3.7
	200 (1.38)	155.0 (1.07)	148.2 (1.02)	+ 4.6

specimens based on 20 - 40% strain and also shows the percent difference between the 4in. (101.6mm) and 2in. (50.8mm) specimens. The results of the 6in. (152.4mm) are omitted because only two tests were performed with this size specimen. The average difference between the two sizes and shape factors is very small with the 2in.(50.8mm) specimen values measuring on average 3.75% greater than the 4in. (101.6mm) values. These results indicate that the 20 - 40% strain relationship tends to negate the effect of the shape factor.

When analyzing these results and comparing them with the results from the initial quad shear tests discussed in Chapter 5, it was surprising to note that the replicate test on the 4in. (101.6mm) specimens from manufacturer A showed an increase in shear modulus values. This relationship was more pronounced based on the Annex A criteria than on the 20 - 40% strain relationship. Table 6.5 compares the results of all the quad shear tests performed on specimens from Manufacturer A.

Table 6- 5 Direct comparison of quad shear tests — anufacturer A

	Shear Modulus psi (MPa) - Manufacturer A			
G_n psi (MPa)	100 (0.69)		200 (1.38)	
Specimen Size	Annex A	20-40%	Annex A	20-40%
2 x 2 x 0.5in. (50.8 x 50.8 x 12.7mm)	148 (1.02)	127.5 (0.89)	210 (1.45)	184.5 (1.29)
* 2 x 2 x 1in. (50.8 x 50.8 x 25.4mm) *	148.8 (1.03)	122.1 (0.84)	212.2 (1.46)	178.9 (1.23)
4 x 4 x 1in. (101.6 x 101.6 x 25.4mm)	139 (0.96)	118 (0.825)	191.5 (1.32)	162 (1.13)
* 4 x 4 x 1in. (101.6 x 101.6 x 25.4mm) *	152.3 (1.05)	122.1 (0.84)	218.9 (1.51)	178.5 (1.23)
* 6 x 6 x 1in. (152.4 x 152.4 x 25.4mm) *	163.7 (1.13)	134.7 (0.93)	212.5 (1.47)	187.3 (1.29)

There are several possible explanations for the increase in shear modulus values. From the physical properties of the initial tests, the average hardness of the material with G_n = 100psi (0.69MPa) and G_n = 200psi (1.38MPa) was 61.1 and 68.9, respectively. The hardness of the material tested one year later was 65.1 and 71.4, respectively. The difference in hardness may account for the increase in shear modulus. It is also important to note that the initial tests were performed shortly after the pads were received from the manufacturer and the follow-up tests were performed on pads that were in inventory for over one year. It appears that bearing stiffness may increase with time (thus the higher hardness values) resulting in higher shear modulus values. The other difference in the two tests was the operator, although each procedure for preparing and testing the specimens was rigorously followed.

6.3 Full Scale Tests - Strain in Two Directions

Full Scale tests from Manufacturers A, B and C were conducted approximately one year after the initial tests were conducted by Muscarella (38). The specimens for these tests were the same utilized by Muscarella. As the purpose of this phase of the investigation was to examine the difference between the ASTM test and the full scale test, only flat specimens were tested. The bearings supplied by Manufacturer A contained two steel shims and Manufacturers B and C supplied three and six shim specimens. The full scale shear modulus values for Manufacturers B and C are the average of the measured values of the three and six shim specimens.

Each specimen was tested according to the procedures established by Muscarella. Steam-cleaned pads were placed in the test apparatus and a 550 psi (3.85MPa) compressive force was applied to hold the pads in place. A horizontal force was applied and the pads were sheared to 50% strain in one direction. The direction of the force was then reversed and the pads were sheared to 50% strain in the opposite direction. The shear modulus was determined from the load displacement curve of the fourth cycle and was calculated utilizing the formula:

$$G = Hh_{rt}/A\Delta s \tag{Eq 6.1}$$

where:

H = horizontal applied force

h_{rt} = elastomer thickness of bearing pad

A = surface contact area of bearing

Δs = horizontal deflection of the bearing

Table 6.6 compares the results with those obtained by Muscarella. The results indicate that the 1995 measured values were on average 18.5% (+/- 8%) greater than the results from tests on the same specimens one year earlier. A comparison of the hardness values revealed that they were nearly identical to the values recorded one year earlier, for example, for Manufacturer A, the hardness values of the 100psi (0.69MPa) specimens remained unchanged at 65.1 and the 200psi (1.39MPa) increased slightly from 71.3 to 71.4. The specimens were the same that were tested in 1994, they were tested in the same manner, and had nearly identical values of hardness. This seems to indicate that the material "cured" over the course of one year and became stiffer.

The only other point of direct comparison, the measured shear modulus values using the ASTM Annex A formula of the 4 x 4 x 1in. (101.6 x 101.6 x 25.4mm) specimens from Manufacturer A with G_n = 100psi (0.69MPa) and G_n = 200psi (1.38MPa), from Table 6.5, shows that measured shear modulus values increased by 8.7% and 12.7% for G_n = 100psi (0.69MPa) and G_n = 200psi (1.38MPa), respectively. Although there was a difference in hardness between the two tested sets, the increase in the shear modulus of the small scale specimens is consistent with the noted increase in the full scale specimens.

A comparison of the 1995 quad shear test results was made with the 1995 full scale test results. Table 6.7 compares the full scale results with the ASTM Annex A and the 20 - 40% strain results. The measured shear modulus values of the 4in. (101.6mm) specimens using the Annex A criteria were 20% higher than the values recorded for the full scale specimens, although the range of the scatter is +/- 9%. When the same comparison is made based on the 20 - 40% strain criteria, the small scale specimens are only 7% higher than the full scale specimens with a scatter of +/- 6%.

The full scale results were adjusted by the α factor as discussed in Section 5.4 (39) and were compared with the results of the 4in (101.6mm) specimens. Two shim specimens from Manufacturer A were assigned an α of 0.8 because it is the lower bound α factor for three shim specimens. Specimens from Manufacturers B and C were assigned an α of 0.9 which is an average α for three and six shim specimens. The adjusted full scale results are

Table 6- 6 Summary of 1994 and 1995 full-scale tests — Manufacturers A, B, and C

Manufacturer	Specified Shear Modulus psi (Mpa)	Shear Modulus of Flat Specimens psi (MPa)		% Chane from 1994
		Initial 1994 Results	1995 Results	
A	100 (0.69)	98.6 (0.68)	120.7 (0.83)	+ 22.4
	200 (1.38)	122.0 (0.84)	155.1 (1.07)	+ 27.1
B	100 (0.69)	86.9 (0.60)	102.9 (0.71)	+ 18.4
	200 (1.38)	139.8 (0.96)	156.3 (1.08)	+ 11.8
C	100 (0.69)	87.2 (0.60)	102.7 (0.71)	+ 17.8
	200 (1.38)	119.0 (0.82)	135.1 (0.93)	+ 13.5

Table 6- 7 Summary of 1995 quad shear tests and full scale tests

Manufacturer	G_n psi (MPa)	Shear Modulus psi (MPa)				
		2 x 2 x 1in. (50.8 x 50.8 x 25.4mm)		4 x 4 x 1in. (101.6 x 101.6 x 25.4mm)		9 x 14 in.* (229 x 356mm)
		ASTM Annex A	20-40% Strain	ASTM Annex A	20-40% Strain	Full Scale Test +/- 50% Strain
A	100 (0.69)	148.8 (1.03)	122.1 (0.84)	152.3 (1.05)	122.1 (0.84)	120.7 (0.83)
	200 (1.38)	212.2 (1.46)	178.9 (1.23)	218.9 (1.51)	178.5 (1.23)	155.1 (1.07)
B	100 (0.69)	130.6 (0.90)	102.4 (0.71)	115.7 (0.80)	92.5 (0.64)	102.9 (0.71)
	200 (1.38)	191.8 (1.32)	155.5 (1.07)	185.4 (1.28)	150.5 (1.04)	156.3 (1.08)
C	100 (0.69)	124.7 (0.86)	110.8 (0.76)	121.6 (0.84)	106.8 (0.74)	102.7 (0.71)
	200 (1.38)	200.6 (1.38)	155.0 (1.07)	184.0 (1.27)	148.2 (1.02)	135.1 (0.93)

* Elastomer thickness was 1.75in. (51mm); overall thickness varied due to different number of shims.

Table 6- 8 Summary of the 4-in. (101.6-mm) specimens and full-scale (adjusted) specimen

Manufacturer	G_n psi (MPa)	Shear Modulus psi (MPa)		
		4 x 4 x 1in. (101.6 x 101.6 x 25.4mm)	4 x 4 x 1in. (101.6 x 101.6 x 25.4mm)	Adjusted Full Scale Test (Full Scale/α)
		ASTM Annex A	20 - 40% Strain	+/- 50% Strain
A	100 (0.69)	152.3 (1.05)	122.1 (0.84)	150.9 (1.04)
	200 (1.38)	218.9 (1.51)	178.5 (1.23)	193.9 (1.34)
B	100 (0.69)	115.7 (0.80)	92.5 (0.64)	114.3 (0.79)
	200 (1.38)	185.4 (1.28)	150.5 (1.04)	173.7 (1.20)
C	100 (0.69)	121.6 (0.84)	106.8 (0.74)	114.1 (0.79)
	200 (1.38)	184.0 (1.27)	148.2 (1.02)	150.1 (1.04)

more closely related to the ASTM Annex A values than to the 20 - 40% strain values (Table 6.8). This is in direct contrast to the analysis in Chapter 5 (Table 5.9) which demonstrated that the adjusted values were quite similar to the 20 - 40% strain values but were significantly smaller than the ASTM Annex A values.

6.4 Modified Full Scale Tests - Strain in One Direction

The same full scale specimens were subjected to another test regimen in order to examine the effect of test method on the measured shear modulus. As was previously noted, the ASTM test sheared the small specimens to 50% strain in one direction while the full scale test sheared the specimens to 50% strain in both directions. In order to test the full scale specimens in a manner more similar to the ASTM test, the full scale test procedure was altered.

The test setup was not modified. Steam-cleaned pads were placed in the test apparatus and the initial position of the bearing was determined and noted. A horizontal force sheared the bearings in one direction to 50% strain. The direction of the force was reversed and the bearings were sheared in the opposite direction until the horizontal force was zero. The new position was recorded, the direction of force was reversed to the initial direction and the bearings were again sheared to 50% strain from the new zero-load position. This procedure was repeated and the shear modulus was determined from the slope of the load displacement curve of the fourth cycle.

The shear modulus was calculated utilizing Equation 6.1 and the ASTM Annex A formula. The difference between these calculated values was less than 1% and the values presented in Table 6.9 are based on Equation 6.1. Table 6.9 compares the measured shear modulus values obtained for the full scale specimens utilizing the +/- 50% strain method and the 50% strain method.

Table 6- 9 Summary of full-scale tests utilizing ± 50% and 50% strain methods

Manufacturer	G_n psi (MPa)	Shear Modulus psi (MPa)		Percent Difference
		Full Scale Test +/- 50% Strain	Full Scale Test 50% Strain	
A	100 (0.69)	120.7 (0.83)	135.3 (0.93)	+ 12.1
	200 (1.38)	155.1 (1.07)	172.5 (1.19)	+ 11.2
B	100 (0.69)	102.9 (0.71)	107.6 (0.74)	+ 4.6
	200 (1.38)	156.3 (1.08)	161.9 (1.12)	+ 3.6
C	100 (0.69)	102.7 (0.71)	107.0 (0.74)	+ 4.2
	200 (1.38)	135.1 (0.93)	145.5 (1.00)	+ 7.7

The results demonstrate that the shear modulus results based on the 50% strain method, which is similar to the ASTM method, are between 3.6% and 12.1% greater than values obtained from the exact same specimens which were tested utilizing the +/- 50% strain method. This indicates that the test method does influence the measured shear modulus value.

Table 6.10 summarizes the shear modulus results of the all the specimens that were tested in 1995 by shearing natural rubber specimens to 50% strain in one direction only. The values indicate that the shear modulus values of the full scale specimens are still lower than those of the smaller specimens.

However, when the full scale results are modified by α as previously described (0.8 for Manufacturer A and 0.9 for Manufacturers B and C) to account for the ends rolling up, the results compare favorably. In four of the six cases in Table 6.10 (three manufacturers, two nominal shear moduli per manufacturer), the α-modified full scale results fall within 3.5% of the measured shear moduli of the 4in. (101.6mm) specimens.

Table 6- 10 Summary of ASTM Annex A (1995) and full-scale 50% strain results

Manufacturer	G_n psi (MPa)	Shear Modulus psi (MPa)			
		2 x 2 x 1in. (50.8 x 50.8 x 25.4mm)	4 x 4 x 1in. (101.6 x 101.6 x 25.4mm)	9 x 14 in. (229 x 356mm)	9 x 14 in. (229 x 356mm)
		ASTM Annex A	ASTM Annex A	50% Strain	50% Strain (α Modified)
A	100 (0.69)	148.8 (1.03)	152.3 (1.05)	135.3 (0.93)	169.1 (1.17)
	200 (1.38)	212.2 (1.46)	218.9 (1.51)	172.5 (1.19)	215.6 (1.49)
B	100 (0.69)	130.6 (0.90)	115.7 (0.80)	107.6 (0.74)	119.6 (0.83)
	200 (1.38)	191.8 (1.32)	185.4 (1.28)	161.9 (1.12)	179.9 (1.24)
C	100 (0.69)	124.7 (0.86)	121.6 (0.84)	107.0 (0.74)	118.9 (0.82)
	200 (1.38)	200.6 (1.38)	184.0 (1.27)	145.5 (1.00)	161.7 (1.12)

6.5 Discussion of Test Results

The preceding discussion and analysis compared the shear modulus results of several types of tests which incorporated different procedural formats and utilized different specimen sizes. There are several noted correlations: (A) Shear modulus values tend to be higher for specimens tested one year after the initial tests, that is, it appears there may a period of time in which the bearing pads "cure" and become stiffer; (B) Neither size nor shape factor seem to affect the shear modulus value when this value is determined from the 20 - 40% strain relationship from the ASTM test; © Straining the bearings in two directions appears to yield lower shear modulus values than straining in one direction only; and (D) The shear modulus values determined by utilizing the ASTM Annex A formula tend to be higher than when determined from full scale specimens tested in one or two directions. If the full scale test in two directions provides the most accurate measurement of the shear modulus, is there a method of accurately predicting this value based on the ASTM tests?

In order to determine an answer, it is important to reduce as many variables as possible. As there seem to be differences depending on the test date, only 1995 results were analyzed, which also reduced the number of test operators to one. The results from Manufacturer A were not included because the specimens had two steel shims while the results from Manufacturers B and C were obtained from specimens with three and six steel shims. Excluding Manufacturer A also eliminated a significant hardness difference because for G_n = 100psi (0.69MPa), A had a hardness of 65.1 while B and C had hardness values of 57.0 and 53.9, respectively. Table 6.11 summarizes the 1995 test results for Manufacturers B and C. It includes the results from the ASTM tests with the shear modulus determined utilizing the Annex A formula and the 20 - 40% strain relationship, and the full scale test results from straining in one and two directions.

The results indicate a correlation between the full scale results when tested in one and two directions. The results of the full scale test in one direction, which corresponds to the ASTM test method, average 5% (+/- 2%) greater than the two-directional test. This would indicate that the ASTM test results should be scaled by 0.95 to correct for this difference in test method. Table 6.11 also indicates that the ASTM results, based on the 20 - 40% strain relationship, seem to be a reasonably accurate indicator of the shear modulus of the full scale specimens when tested in two directions. Table 6.12 illustrates this relationship. The results based on the 20 - 40% strain relationship were not scaled and the percent difference is based on the difference between the small and the full scale specimens.

Table 6- 11 Summary of 1995 results — Manufacturers B and C

Manufacturer	G_n psi (MPa)	Shear Modulus psi (MPa)							
		2 x 2 x 1in. (50.8 x 50.8 x 25.4mm)		4 x 4 x 1in. (101.6 x 101.6 x 25.4mm)		Full Scale +/-50% Strain		Full Scale 50% Strain	
		Annex A	20 -40%	Annex A	20 -40%	Actual	α Mod.	Actual	α Mod.
B	100 (0.69)	130.6 (0.90)	102.4 (0.71)	115.7 (0.80)	92.5 (0.64)	102.9 (0.71)	114.3 (0.79)	107.6 (0.74)	119.6 (0.83)
	200 (1.38)	191.8 (1.32)	155.5 (1.07)	185.4 (1.28)	150.5 (1.04)	156.3 (1.08)	173.7 (1.20)	161.9 (1.12)	179.9 (1.24)
C	100 (0.69)	124.7 (0.86)	110.8 (0.76)	121.6 (0.84)	106.8 (0.74)	102.7 (0.71)	114.1 (0.79)	107.0 (0.74)	118.9 (0.82)
	200 (1.38)	200.6 (1.38)	155.0 (1.07)	184.0 (1.27)	148.2 (1.02)	135.1 (0.93)	150.1 (1.04)	145.5 (1.00)	161.7 (1.12)

Table 6- 12 Summary of 20-40% strain and full-scale results - Manufacturers B and C

Manufacturer	G_n psi (MPa)	Percent Difference (2in. from full scale)	Shear Modulus psi (MPa)			Percent Difference (4in. from full scale)
			20 - 40% Strain	+/-50% Strain	20 - 40% Strain	
			2 x 2 x 1in. (50.8 x 50.8 x 25.4mm)	9 x 14 in. (229 x 356mm)	4 x 4 x 1in. (101.6 x 101.6 x 25.4mm)	
B	100 (0.69)	- 0.5	102.4 (0.71)	102.9 (0.71)	92.5 (0.64)	- 10.1
	200 (1.38)	- 0.5	155.5 (1.07)	156.3 (1.08)	150.5 (1.08)	- 3.7
C	100 (0.69)	+ 7.9	110.8 (0.76)	102.7 (0.71)	106.8 (0.71)	+ 4.0
	200 (1.38)	+ 14.7	155.0 (1.07)	135.1 (0.93)	148.2 (1.02)	+ 9.7

The results demonstrate that the average difference in shear modulus values between the 2in. (50.8mm) and the full scale specimens is 6%, and for Manufacturer B, the shear modulus values are nearly identical. The average difference between the 4in. (101.6mm) and the full scale specimens is 7%. It is also interesting to note the variation by manufacturer. The small specimens from Manufacturer B had shear modulus values slightly less than the measured values of the full scale specimens while the shear modulus values of the small specimens from Manufacturer C were greater than the measured values of the full scale specimens.

A similar comparison was made with the ASTM Annex A results. These results were scaled by a factor $\beta = 0.855$, which is a combination of two factors; 0.95 to account for the difference in test method, and an α factor of 0.9 as previously discussed. Table 6.13 compares the scaled Annex A results with the full scale two-directional results.

The results indicate that scaling the 4in. (101.6mm) ASTM Annex A results to account for differences in test method and the noted difference between glued pads and friction-held pads seems to reasonably predict full scale results. The exception is Manufacturer C, G_n = 200psi (1.38MPa), although ASTM D4014 notes that the shear modulus may be overestimated for elastomers with a hardness greater than 55 and this specimen has a hardness of

Table 6- 13 Comparison of scaled Annex A and ± 50% full-scale results

Manufacturer	G_n psi (MPa)	% Difference (2in. from full scale)	Shear Modulus psi (MPa)			% Difference (4in. from full scale)
			2 x 2 x 1in. (50.8 x 50.8 x 25.4mm) $\beta = 0.855$	9 x 14 in. (229 x 356mm)	4 x 4 x 1in. (101.6 x 101.6 x 25.4mm) $\beta = 0.855$	
B	100 (0.69)	+ 8.6	111.7 (0.77)	102.9 (0.71)	98.9 (0.68)	- 3.9
	200 (1.38)	+ 4.9	164.0 (1.13)	156.3 (1.08)	158.5 (1.09)	+ 1.4
C	100 (0.69)	+ 3.8	106.6 (0.74)	102.7 (0.71)	104.0 (0.72)	+ 1.3
	200 (1.38)	+ 26.9	171.5 (1.18)	135.1 (0.93)	157.3 (1.09)	+ 16.4

69.5 (23). If the exception is not included, both the 2in. (50.8mm) and the 4in. (101.6mm) values are within 10% of the full scale specimens but the values of the 4in. (101.6mm) specimens represent a greater correlation with the full scale specimens.

6.6 Summary

Two methods of determining the shear modulus of the full scale specimens based on the quad shear test results have been presented. Both methods appear to reasonably predict the shear modulus values of the full scale specimens within 10% whether the quad shear specimen size is 2 x 2 x 1in. (50.8 x 50.8 x 25.4mm) or 4 x 4 x 1in. (101.6 x 101.6 x 25.4mm). The overall correlation based on the 20 - 40% linear relationship seemed to have less variation and a tighter scatter than the correlation based on the scaled Annex A values, however, the 20 - 40% method is limited to comparing full scale specimens that are not adhered to the contact surfaces. The best correlation appears to be between the full scale results and the 4 x 4 x 1in. (101.6 x 101.6 x 25.4mm) results when the 4in. (101.6mm) specimens are scaled by 0.95 to account for the directional difference and an appropriate α value, realizing that for G_n of 200psi (1.38MPa), this value may be an overestimate. The latter method of determining the shear modulus is more versatile than the 20 - 40% method because one can account for variations in the contact surfaces (adhered or friction-held). It is important to note that these noted trends were not confirmed by additional tests and that these correlations may be valid for elastomers within a certain band of hardness values.

CHAPTER 7

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

7.1 Summary

In this study, natural rubber blocks from Manufacturer A 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 were presented in Chapter 4 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 were fully presented in Chapter 5 of this report. Additional shear modulus tests were conducted on natural rubber specimens from Manufacturers A, B and C, with G_n values of 100psi (0.69MPa) and 200psi (1.38MPa), measuring 2 x 2 x 1in. (50.8 x 50.8 x 25.4mm), 4 x 4 x 1in. (101.6 x 101.6 x 25.4mm), and 6 x 6 x 1in. (152.4 x 152.4 x 25.4mm). Shear modulus tests were also conducted on full scale natural rubber specimens from the same manufacturers measuring 9 x 14in. (229 x 356mm) with an elastomer thickness of 1.75in. (44.5mm). The results of these tests are presented in Chapter 6.

7.2 Conclusions

After performing the initial 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 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. It is concluded that the shear modulus value of a NR block is not affected by an increase in the compressive stress. 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. Test results also indicated that calculating the shear modulus from this linear portion of the curve tended to negate the affect of specimen size. Additional tests indicated that the shear modulus values from the quad shear test determined from the linear relationship between 20 - 40% strain may predict within 10% the shear modulus of full scale pads which are not fixed to the contact surfaces. Tests on full scale specimens indicated that shear modulus values obtained from one-directional straining were 5% higher than two-directional straining. The analysis of the quad shear and the full scale tests indicate that the best method for determining the shear modulus of full scale pads based on the quad shear test is to use 4 x 4 x 1in. (101.6 x 101.6 x 25.4mm) specimens, determine the 4in. specimen's shear modulus from the Annex A formula, and adjust this value by 0.95 to account for directional differences and an appropriate α factor.

7.3 Recommendations

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. It appears that the preferred specimen size is 4 x 4 x 1in. (101.6 x 101.6 x 25.4mm). The engineer can adjust this value, as described above, to account for the number of shims in the pad or the bearing pad being fixed to the contact surfaces.

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.

The correlations noted in this report are an indication of a relationship between the quad shear test and full scale bearings. Although the pads were requested by specific values of shear modulus, the calculated values demonstrated a high degree of variability between the different products, especially with regard to pads with a G_n of 200psi (1.38MPa). Future studies of various manufacturers' products are required to demonstrate a conclusive relationship between the quad shear test and full scale bearings.

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