NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM
REPORT **109**

ELASTOMERIC BEARING RESEARCH

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM
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ELASTOMERIC BEARING RESEARCH

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COLUMBUS, OHIO

RESEARCH SPONSORED BY THE AMERICAN ASSOCIATION
OF STATE HIGHWAY OFFICIALS IN COOPERATION
WITH THE FEDERAL HIGHWAY ADMINISTRATION

SUBJECT CLASSIFICATIONS:
BRIDGE DESIGN
GENERAL MATERIALS

HIGHWAY RESEARCH BOARD
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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Systematic, well-designed research provides the most effective approach to the solution of many problems facing highway administrators and engineers. Often, highway problems are of local interest and can best be studied by highway departments individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation develops increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

In recognition of these needs, the highway administrators of the American Association of State Highway Officials initiated in 1962 an objective national highway research program employing modern scientific techniques. This program is supported on a continuing basis by funds from participating member states of the Association and it receives the full cooperation and support of the Federal Highway Administration, United States Department of Transportation.

The Highway Research Board of the National Academy of Sciences-National Research Council was requested by the Association to administer the research program because of the Board's recognized objectivity and understanding of modern research practices. The Board is uniquely suited for this purpose as: it maintains an extensive committee structure from which authorities on any highway transportation subject may be drawn; it possesses avenues of communications and cooperation with federal, state, and local governmental agencies, universities, and industry; its relationship to its parent organization, the National Academy of Sciences, a private, nonprofit institution, is an insurance of objectvity; it maintains a full-time research correlation staff of specialists in highway transportation matters to bring the findings of research directly to those who are in a position to use them.

The program is developed on the basis of research needs identified by chief administrators of the highway departments and by committees of AASHO. Each year, specific areas of research needs to be included in the program are proposed to the Academy and the Board by the American Association of State Highway Officials. Research projects to fulfill these needs are defined by the Board, and qualified research agencies are selected from those that have submitted proposals. Administration and surveillance of research contracts are responsibilities of the Academy and its Highway Research Board.

The needs for highway research are many, and the National Cooperative Highway Research Program can make significant contributions to the solution of highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement rather than to substitute for or duplicate other highway research programs.

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This report was prepared by the contracting research agency. It has been reviewed by the appropriate Advisory Panel for clarity, documentation, and fulfillment of the contract. It has been accepted by the Highway Research Board and published in the interest of effective dissemination of findings and their application in the formulation of policies, procedures, and practices in the subject problem area

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FOREWORD

By Staff

Highway Research Board

This report is recommended to bridge design engineers, specifications writers, research engineers, rubber technologists, and others interested in the behavior of elastomeric bearings for engineering applications. The report presents the results of a reasonably extensive experimental program on elastomeric bearings of three different materials tested under a variety of situations. Suggestions are offered for those sections of the AASHO *Standard Specifications for Highway Bridges* dealing with elastomeric bearings.

The development of new elastomers and elastomeric bearing systems is proceeding at a rapid rate. The ability of these bearings and bearing systems to absorb the various loads and movements occurring in bridges in a more efficient manner and at a significantly lower cost than mechanical bearing systems justifies an effort to improve current designs. To achieve this objective, research was contemplated to evaluate materials for elastomeric bearings as defined in the AASHO *Specifications.* This research was to include a thorough survey of the available literature and test data on elastomeric materials and bearing systems. The research contemplated reasonably extensive laboratory testing conducted on various bearing arrangements and configurations under conditions simulating as nearly as practicable actual bridge conditions.

In response to the foregoing stated desires, the Battelle Memorial Institute undertook NCHRP Project 12-9 with the objectives of evaluating the effects of geometry on compressive strain, compressive set, shear modulus, and rotational modulus of elastomers with hardness between 50 and 70 durometer by testing realistic size specimens. The researchers also studied the effects of lamination, the relative performance of glued laminated pads compared to fully vulcanized units, the relative performance of molded bearings versus bearings sawed from larger sheets, and an evaluation of the aging and low-temperature characteristics of various elastomers.

The report describes in detail how the experimental work was conducted and the significance of the results as applied to design criteria in common use today. As is well known, the design and development of elastomeric bridge bearings has been traditionally empirical, with the result that conflicts exist throughout current specifications and practices. The researchers attempted to resolve this situation by validating theoretically generated design criteria, hence producing more rational and realistic design methods. This effort to transform an empirically based semi-science into theoretically sound rational design criteria produced interesting and unexpected results.

Based on the research findings, several modifications to the current AASHO *Specifications* are suggested. In any case, the research results do offer insight into the significance of the physical properties of elastomeric materials and also an insight into the geometry-related behavior of those materials when assembled into elastomeric bearing systems.

The research has brought to light the need for further studies into the crystallization phenomenon, the identification of physical properties in elastomeric materials that will guarantee satisfactory field performance, the need for using a statistically designed experiment to evaluate interrelationships between various parameters, and additional work to develop a theoretical predictive method that can adequately describe the performance of elastomeric bearing systems.

CONTENTS

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The research reported herein was conducted at the Battelle Memorial Institute by personnel of the Heavy Structures and Equipment Division and, subsequently, the Applied Solid Mechanics Division. Richard A. Egen, Senior Scientist, and John C. Minor, Research Mechanical Engineer, were the principal investigators. Assisting Messrs. Egen and Minor during the research were Hobart A. Cress, Chief, Heavy Structures and Equipment Division; William J. Mueller, Research Chemist, Rubber and Plastics Division; and Robert Goldsmith, Structural Engineer, Associate with the Ammann and Whitney Company, New York.

Product samples and research suggestions were supplied by the following persons: T. D. Eubank, E. I. du Pont de Nemours and Company (through the Oil States Rubber Company); E. P. Pinigis and S. T. Semegen, Natural Rubber Bureau; J. Abbott, Uniroyal, Inc.; and C. H. Neff and R. P. Schwartz, General Tire and Rubber Company. In addition, the following persons contributed directly to the various research areas: A. L. Elliot and E. F. Nordlin, California Division of Highways; R. Perry, New York Department of Transportation; W. G. Henneberger, Texas Highway Department; J. N. Clary, Virginia Department of Highways; A. H Johnson, Armstrong Cork Company; S. W. Schmitt, E. I. du Pont de Nemours and Company; W. L. Williams, Enjay Chemical Company; W. Clark, Goodyear Tire and Rubber Company; Dr. A. Gent, University of Akron; W. W. Aldridge, University of Oklahoma; H. L. Kinnear, University of Virginia; and Dr. C. G. Moore and A. G. Thomas, Natural Rubber Producers' Research Association.

The assistance of many other persons in state highway departments, manufacturing firms, and universities is gratefully acknowledged.

ELASTOMERIC BEARING RESEARCH

SUMMARY

The design and development of elastomeric bridge bearings has been almost entirely empirical. It is therefore difficult to judge the potential of new materials without testing. An effort was made to define and separate those parameters that significantly affect the behavior and performance of elastomeric bridge bearings, to accomplish the general objective of improving current designs. The research included a survey of the literature and available test data, an evaluation (testing) program, and the analysis of data generated. The evaluation program investigated (1) shear modulus and stress relaxation, (2) compressive behavior, (3) shear and compression of commercial bearings, and (4) cyclic shear under constant compression. The major work was accomplished with 50- to 70-durometer neoprene bonded to steel and neoprene bonded to dacron; some limited testing was done with natural rubber and ethylene propylene dimonomer (EPDM). Shear of neoprene was investigated down to −40 F. Compression tests included a range of shape factors from 1 to 15 and a range in number of laminates from 1 to 18.

The survey of literature and available test data revealed that the state of the art is empirical in nature, and that many conflicts exist regarding current specifications and practices. Design information on shape-related elastomeric bearing behavior is meager. Only limited usable materials properties information is available; current materials specifications are quality- rather than performance-related. Little effort has been made to validate empirical predictions with actual bearing field performance.

Although there may be some question regarding the confidence that may be placed in the experimental findings, due to a limited amount of testing on a wide range of parameters, these findings may be considered a further extension of the understanding of elastomeric bridge bearing performance. It was found, as expected, that the higher the durometer hardness, the greater the shear modulus; there was some disagreement with published curves. Lower temperatures produced a marked nonlinear increase in the shear modulus of neoprene. Stress relaxation in shear showed a general increasing trend with increased shear modulus and, therefore, also with decreased temperature. A large increase in shear modulus (probably due to crystallization) with time at low temperatures was noted for neoprene; the greatest increase occurred at about −20F. Size and shape did not affect shear modulus to any significant degree, provided bending of tall bearings was properly accounted for. A relationship between shape factor and compressive strain for bonded elastomeric bearings was developed for several values of hardness; there was significant deviation of these results from both empirical (shape factor approach, *2*) and theoretical predictions (*4, 5*). An explanation of these predictive methods appears in Appendix F. The theoretical approach appeared valid for low shape factors; the empirical approach, for intermediate shape factors; and neither,

for high shape factors. Bonded, laminated compressive behavior was predictable from the results for a single laminate. For neoprene bonded to dacron, the greater the number of laminations, the greater the compressive strain for the same average stress. Holes in bearings affected compressive behavior as predicted by the change in shape factor. No discernable variations in shear modulus were found through sections of commercial bearings. A small decrease in shear modulus was evident as a result of shear cycling under constant compression. Compressive creep under shear cycling showed higher creep for greater hardness values. Possibly because of laboratory technique, fully vulcanized bonds proved better than glued bonds. No problem was encountered in shear-cutting elastomeric sheet stock, or cutting through elastomer-steel laminates.

In view of the findings, several modifications of the current American Association of State Highway Officials (AASHO) *Standard Specifications for Highway Bridges* (10th ed., 1969) are suggested, so that these specifications will more closely agree with desired performance and material property requirements. Application of the research results should lead to a better understanding of the importance of the various design parameters, particularly in the area of shape-related behavior.

Recommended research areas include the following: (1) effects of time and temperature on the crystallization of elastomers, (2) over-all materials properties evaluation leading to standard bridge bearing compounds, (3) field evaluation of elastomeric bearing performance, (4) a statistical approach to the evaluation of shape-related effects on bonded bearing behavior, and (5) a continued effort to develop a viable theoretical formulation of bearing behavior under all modes of loading.

CHAPTER ONE

INTRODUCTION AND RESEARCH APPROACH

DESCRIPTION OF THE PROBLEM

The state of the art with regard to the design and development of elastomeric bridge bearings can be characterized in general as being an empirical discipline. The lack of a commonly accepted basic analytical method for describing the behavior of elastomeric bridge bearings has resulted in divergent opinions regarding the design criteria that should be applied. Because the nature of the interaction of the various material and shape-related parameters is not clearly understood, the empirical developments have led to conflicts among the various design criteria, even though satisfactory bearing designs have been developed.

Furthermore, because developments have been empirical and have been concerned primarily with neoprene and natural rubber, it is difficult to judge the potential use of new materials without considerable additional testing of bearings. Such testing is vital because the properties of the new materials that are important, and the degree to which they are important, are not generally known or cannot be related meaningfully to previous experience.

The need, then, is for an effort to define and separate the various parameters in the design of elastomeric bridge bearings which significantly affect their behavior and performance. The problem centers around the bridge designer.

Unless he can at least understand the short- and long-term behavior of elastomeric bearings, he will not allow their use. Their potential to absorb the various loads and movements occurring in bridges in a more efficient manner and at significantly lower cost than mechanical systems will remain unrealized. While understanding may seem important, the ability to predict behavior within engineering accuracy is mandatory as it affects the design and performance of the bridge installation as a whole

OBJECTIVES OF THE RESEARCH

The general objective of the research was to improve current designs of elastomeric bridge bearings. Implicit in this general objective is the development both of a qualitative and a quantitative understanding of the behavior of bearings under all conditions that are likely to be encountered in actual service. Also implicit is the realization of a predictive method for judging alternate bearing designs, either empirically or theoretically. Once these objectives have been fulfilled, the bridge design engineer will be able to judge more rationally the relative merits of specific bridge bearing recommendations.

Specific objectives outlined in the original project statement and covered by the research plan include evaluation of the effects of both shape factor and laminations on compressive strain, compressive set, shear modulus, and rotational modulus of elastomeric bridge bearings Also included were performance evaluations of glued versus fully vulcanized laminates, and molded pads versus pads sawed from large sheets. Another major objective was the evaluation of aging and low-temperature characteristics of various pads. Several minor objectives covered both material properties and geometric (shape-related) behavior.

RESEARCH PLAN

The original research plan was divided into four major tasks, as follows:

1. Task 1—Literature survey and survey of available test data.
2. Task 2—Test planning and equipment design.
3. Task 3—Evaluation program.
4. Task 4—Data analysis and final report.

At the conclusion of Task 1 it was apparent that some of the original objectives had to be modified to develop meaningful information on the behavior of bonded elastomeric bridge bearings. Because of the value to the designer of having a practical, valid design methodology, and because several conflicting empirical and theoretical approaches were available, it was decided to tailor an experimental evaluation program to cover two major areas; these were material properties and geometric behavior. The approved research plan investigated the following aspects of bonded bridge bearing performance:

Group A: Shear Modulus and Stress Relaxation.
Group B: Compression Behavior.
Group E: Commercial Bearings, Shear and Compression.
Group F: Cyclic Shear Under Constant Compression.

In the area of material properties, Group A investigated the effects of time, temperature, and previous history on the shear modulus of natural rubber and EPDM (ethylene propylene dimonomer) at room temperature, and neoprene and neoprene-dacron combination at temperatures between —40 F and +75 F. Stress relaxation was studied by holding samples at constant shear strain and monitoring the load-versus-time behavior. These experiments were carried out in an effort to obtain material property data for use in the other experimental groups, as well as to investigate these properties from the standpoint of actual elastomeric bridge bearing use.

Group B experiments covered a parametric evaluation of compressive bearing behavior. Geometry, lamination, and holes were varied on samples ranging in size from laboratory specimens (down to 9 sq in.) to full size (up to 266 sq in.). Materials were neoprene, natural rubber, and EPDM bonded to steel plates, and neoprene-dacron combination Shape factors ranged from about 1 to 15, number of laminations ranged from 1 to 18, and hardness ranged between 50- and 70-durometer. All tests were run at room temperature. In all cases, compressive stress-strain behavior was compared to that predicted by both theoretical and empirical approaches.

The Group E experiments covered the behavior in shear and compression of commercial bridge bearings of two types: neoprene vulcanized and bonded to steel plates, and neoprene vulcanized and bonded to dacron sheets. The test conditions were designed to simulate actual bridge bearing emplacement as nearly as possible, but without rotation or temperature changes. Tests were run in shear under constant compression between concrete surfaces to shear strains of ±50 percent, and in compression-only to 2,000 psi stress. An attempt was made to determine the variation in elastomeric material properties throughout the bulk of each bearing. In all cases, compressive stress-strain behavior was compared to that predicted by both theoretical and empirical approaches.

The Group F experiments covered the behavior of laboratory-size sample bearings under constant compressive load and high-rate cycling of shear strain from +50 percent to —50 percent. The bearing materials were neoprene, natural rubber, and EPDM bonded to steel plates, and neoprene-dacron combination placed between steel plates. Hardness was nominally 50-durometer, with the exception of neoprene, which was tested in 50-, 60-, and 70-durometer. Bearings were sheared cyclically and continuously for more than two days each to observe the effects on shear modulus and also on compressive creep.

Table 1 gives the formulation and physical properties of elastomeric materials.

TABLE 1

FORMULATION AND PHYSICAL PROPERTIES—ELASTOMERIC MATERIALS

Neoprene (S, Oil States Rubber Co , Arlington, Texas)

Compounding formulation   proprietary information

Physical properties   meet or exceed all applicable AASHO and State of Texas specifications

Neoprene-Dacron (D, Goodyear Tire & Rubber Co , Los Angeles, California)

Compounding formulation·   proprietary information

Physical properties   meet or exceed all applicable State of California specifications

Neoprene (S - Group E only, General Tire & Rubber Co , Wabash, Indiana)

Compounding formulation   proprietary information

Physical properties

ORIGINALS	GTR COMPOUND	AASHO REQUIREMENTS
Tensile, psi	2685	2500
Elongation, %	500	375
Durometer	53	55±5
Tear, ASTM Die C	188	None
AGED PHYSICALS, 70 hr @ 212° F		
Tensile, psi	2680	
Tensile Change, %	No change	-15% Max
Elongation, %	430	
Elongation Change, %	-14 0	-40% Max
Durometer	60	
Durometer Change, pts	+7	+15 pts Max
COMPRESSION SET, ASTM D395 METHOD B		
22 hrs @ 158° F, %	7 9	None
22 hrs @ 212° F, %	22 9	35% Max

OIL RESISTANCE, 70 hr @ 212° F, ASTM #3 OIL	GTR COMPOUND	AASHO REQUIREMENTS
Volume Change, %	82 4	None
ADHESION, ASTM D429B		
Lbs/Inch of Width	76	40 min
LOW TEMPERATURE, ASTM D746		
3 Min @ -40° F	OK-Not Brittle	None
OZONE RESISTANCE, 100 hrs @ 100 pphm @ 100° F		
20% Strain	OK-No Cracks	No cracks

Natural Rubber (N, Natural Rubber Bureau, Hudson, Ohio)

Compounding formulation

	A	B	C
RSSI	100	100	100
Zinc oxide	6	10	30
Stearic acid	1	1	1
Dutrex R	2	2	2
PBNA	1	1	1
Lampblack	15	35	60
Sulphur	2 5	2 5	2 5
CBS (Santocure)	0 7	0 7	0 7
Antiozonant (UOP 88)	4	4	4
Vulcanization time, mins at 286°F	20	20	20

Physical properties·

TEST RESULTS

Hardness IRHD				
Unaged	degrees	51	60 5	70 5
*Ageing change	degrees	+2	+2 5	+1 5

* Ageing· 7 days at 158° F

Tensile Strength				
Unaged	lb/in^2	3250	3050	2375
*Ageing change	% of unaged value	+5 8	+4 9	NIL
Elongation at Break				
Unaged	%	605	520	380
*Ageing change	% of unaged value	-5 8	-7 7	-10
Compression Set				
% of imposed compression		24	20	28

Weathering   no cracking after ten weeks' exposure

Bond Strength (90° Stripping Test)   Adequate bond strength obtained on test using Chemlok 220

* Ageing 7 days at 158° F

Ethylene Propylene Dimonomer (E, Uniroyal Chemical, Naugatuck, Conn)

Compounding formulation

	J	K	L
ROYALENE 502	80	100	100
ROYALENE 400	40	--	--
Sunthene 3120	40	45	40
HAF	55	65	80
Protox 168	5	5	5
Stearic Acid	1	1	1
Sulfur	0 6	0 4	0 4
TUEX	7	7	7
E TUEX	7	7	7
Tetrone	7	7	7
Sulfasan R	1 5	1 5	1 5
ML-4 @ 212° F	30	33	45
MS @ 250° F 3 pt rise	>30	>30	>30

Physical properties·

		J	K	L
		Tensile Data, psi, Unaged		
Cured @ 340° F				
200% Modulus	30'	370	610	1010
	45'	350	620	1030
300% Modulus	30'	780	1110	1750
	45'	720	1120	1740
Tensile	30'	2100	2430	2650
	45'	2100	2420	2400
Elongation	30'	550	540	460
	45'	540	540	420
Shore A Durometer Hardness	30'	51	61	69
	45'	51	61	69
Tear Die C	30'	260	330	370
	45'	270	320	350
		Tensile Data, psi 70 hrs @ 212° F		
Cured @ 340° F				
Tensile	30'	1880	2410	2510
	45'	2060	2420	2540
Elongation	30'	450	490	380
	45'	490	500	410
Shore A Hardness	30'	52	62	71
	45'	53	62	71
		Compression Set, % of Original Deflection Method B		
		Aged 22 hrs @ 158° F		
Cured @ 340° F	30'	14	12	14
	45'	14	13	13
		Aged 22 hrs @ 212° F		
Cured @ 340° F	30'	29	25	26
	45'	24	20	22

CHAPTER TWO

RESEARCH FINDINGS

THE STATE OF THE ART OF THE USE OF ELASTOMERIC MATERIALS IN BRIDGE BEARINGS

The User

The state of the art with respect to the users of elastomeric bridge bearings is characterized by a wide range of opinions about the way elastomeric materials can be used in bridge bearings. This wide range of opinions is evident in the specifications for bridge bearings of the various state highway departments. Furthermore, there are states that use no elastomeric bearings at all. Because matters of highway construction are relegated primarily to the authority of the individual states in the United States, in contrast with British and Continental practices, differences in specifications from state to state are to be expected. The various state highway specifications are, for the most part, concerned with two separate aspects of the problem—the design of elastomeric bridge bearings and the control of the quality of the elastomeric materials to be used. In matters of quality control, state-to-state differences naturally were expected. When the various design specifications are examined, however, the state-to-state variations are most unexpected.

If design specifications can be regarded as limits set in accordance with the best available knowledge of problems involved, then state-to-state variations are disturbing because there are so many conflicting opinions regarding the best way to design a bridge bearing.

Some of the more interesting variations in bearing design are illustrated by the following situations that occur in practice:

1. In some states, only molded, laminated bearings are used, and these bearings must have a layer of rubber over the vertical surfaces covering the steel sheets. In other states, laminated bearings are fabricated from vulcanized sheet stock and are used with the steel plates fully exposed. On the other hand, dacron cloth is sometimes used rather than steel plate in fabricating laminated bearings.
2. In some states, laminated bearings up to about 4 in. in height are used. In others, laminated bearings as tall as 18 in. are in use.
3. In some states, rubber laminae do not exceed ½ in. in thickness. In others, rubber laminae ¾ in. thick are widely used.

In an attempt to understand the situation, the bases for the majority of the design specifications were sought. Findings reveal that the bases for the majority of the design specifications were (1) unknown, (2) experimentally established years ago and unquestioned since, (3) established by recent experimental results, or (4) suggested by design guides based on other experimental results.

The key to the problem is the word "experimental." Investigation of the situation has shown that, in practice, the design of elastomeric bridge bearings has been and appears to continue to be an empirical discipline almost completely—in short, try something; if it doesn't work, try something else. To be sure, continued experience may narrow the available choices for trial. But if a problem is complex, a purely empirical approach may never resolve the issue. Nevertheless, with a basically empirical approach, different investigators can be expected to find different solutions. However, the variety of solutions creates a problem for the prospective user—a problem of how to determine which solution is applicable for his particular situation.

In addition to delving into the bases of design specifications, the researchers sought information concerning the behavior of bearings in use under bridges. For example, because creep or continued deflection under fixed load is an area of concern in the use of elastomeric bearings, quantitative field data regarding compressive deflection were sought from various users. Shear-deformation variations through the year also were sought. Unfortunately, no such quantitative data have been found. Some states report plans to obtain quantitative field-performance data, but no experimental results were available in time for use in this program.

Although quantitative data were lacking, much useful qualitative information was obtained. Such information is of general use because it presents specific situations that point out the need for an approach to bearing design which is not empirical alone. For example, it has been learned that unpinned bearings under bridges slip under shear loads, and that at times they tend to rotate around some vertical axis. This motion occurs in spite of attempts during design to prevent such motions. As another example, it has been learned that sometimes bearings are only partially loaded on their upper surfaces because the bearings do not tend to accommodate the camber in the bridge beams.

In summary, it has been determined that the historical development of the use of elastomeric bridge bearings in the United States has been almost entirely empirical in nature. And while this approach has been generally successful, it has also spawned a multiplicity of bearing designs and design specifications that are often at variance with one another. It is apparent that the majority of these conflicts results from the absence of fundamental technical understanding (or its equivalent, a valid theoretical description) of the behavior of elastomeric bridge bearings. In addition, quantitative field-performance data are lacking.

The Bearing Fabricator

At the outset, it must be stated that the remarks in this section do not apply to elastomeric bridge bearing fabricators in general, because not all of them were contacted. A sufficient number of discussions did occur, however, to gain insight into the over-all problem.

In the case of bearing fabricators, it again appears that their development efforts have been predominantly empirical. In several cases, the fabricators' efforts are directed toward providing a range of bearing designs for a known range of more or less common types of applications. In general, these efforts must be considered successful, and they are backed up by experimentation. Because rubber technologists, as well as engineers, have been involved, most of the aspects of the peculiarities of the nature of rubber appear to have been given some consideration in the design development efforts.

Again, through empirical development efforts, sets of suitable elastomeric bridge bearing designs have been evolved. In the case of some fabricators, their considerable development efforts have been the basis of some of the design specifications for various state highway departments as well as the AASHO specifications.

The bases of certain design criteria were also sought from the fabricators. It has been found that some criteria were established some time ago through experimentation by fabricators directed toward acceptable bearing behavior. There is no basic argument with any of the established working bearing designs. However, there are reasonable grounds for stating that empirical efforts alone can limit the application of elastomeric bridge bearings to situations that are compatible with existing designs. Illustrative of this potential limitation is the following situation. In the United States, there is apparent universal acceptance of the design criterion that limits the average applied vertical compressive stress to 800 psi dead and live load. A recent and apparently successful Australian application of elastomeric bridge bearings as part of a sizable elevated-roadway structure uses an average applied vertical compressive stress of about 1,850 psi.

It is recognized that allowable concrete compressive stresses (or, in the case of steel sections, allowable flange loading) do represent one limit for the average compressive stress load on a bridge bearing. However, the 800-psi limit currently used did not result from direct concern about the concrete compressive stresses (or for that matter, about flange loads). On the other hand, the 800-psi figure is not the result of direct concern with the strength limitations of any part of the bearing. Experience showed that it was one value that gave acceptable bearing behavior. One does not argue with success, but one can argue with design criteria that are not consistent with other successes: viz., 1,850 psi versus 800 psi.

Another aspect of the over-all problem, which was brought to light during discussions with fabricators, deals with the "credibility gap" between fabricators and prospective users. That is, despite the fact that a fabricator can support predictions for the performance of his bearings with test data and knowledge of rubber technology unavailable to most users, the prospective user may not be convinced that the bearings will behave as the fabricator says they will. There are many conceivable reasons for such a situation occurring. However, it appears certain that an important contributing factor is the lack of a general procedure by which the expected behavior of various bearing designs can be evaluated on a common basis—in short, the lack of a recognized, valid, analytical procedure.

In summary, the development of designs for elastomeric bridge bearings by fabricators of bearings has also been largely empirically directed, but on a more profound level insofar as an understanding of the behavior of rubber is concerned. Even so, there is conflict as to what design criteria should be applied. While some of the debate is involved with the physical properties of rubbers, part appears definitely attributable to the absence of a theoretical method that can predict the behavior of elastomeric bridge bearings hand in hand with the experimental work.

Material Producers

It is well known that large contributions to the development of the use of elastomeric materials in bridge bearings in the United States have been made by the producers of elastomeric materials. Not only were experimental investigations conducted, but design guide books were prepared and issued.

Again the bases for various aspects of the design guidelines were sought, and again it was found that the bases are obscure in history or are the results of previous testing. It is not possible to determine whether certain guidelines represent material strength or stability limitations determined through testing, or if they are just figures representative of some suitable design performance.

During discussions with material producers, yet another aspect of the over-all problem appeared. When the researchers asked for material samples for the experimental portion of this program (particularly for materials other than natural rubber and neoprene), a typical response by material producers was something like, "Tell us what you want in a material, and we'll see if we have it. We have many compounds that might be suitable. For that matter, we could compound a material to your specifications." Following this line, it was stated that the material should have (1) shear modulus (G) value of about 160 psi at room temperature, (2) preferably no change in G with temperature, but, if G did change with temperature, the variation should be known, (3) creep characteristics of such a nature that for fixed shear loads the continued shear deflection does not exceed about 3 percent of the deformation-at-1-hr in a 10-hr period, and (4) compatibility with present AASHO material specifications. The general type of response to such a request is that it might be relatively easy to meet the AASHO specifications, but it is doubtful that the data for all of the first three requirements would be known.

It was pointed out and was generally agreed that, from the bearing-designer's viewpoint, the G and creep information was of more value than the hardness or the tensile failure strength. It was further pointed out and generally agreed that AASHO-like material specifications are established to assure quality control after a useful material is found, but the material specifications do not necessarily give the kinds of information that a producer could use in developing a new compound

It appears that the kinds of material-property information necessary for designing a bearing are not commonly considered by the rubber industry when it is researching a new compound. Compounds are still most often first described in terms of hardness, tensile stress at some elongation, compressive set, etc., and not in the associated terms of shear modulus, yield or breaking stress, and creep or some equivalent.

To summarize, it has been found that the approach of material producers has also been almost completely empirical; that certain aspects of suggested design rules are not necessarily based on material strength or stability limitations, but result directly from historical empirical developments. Furthermore, in general, the kinds of material property characterizations used by the industry are *related to* what is considered necessary for bearing design, but often they are *not usable per se.* To obtain what is considered usable for design requires tests that are not generally performed and, in some cases, tests for which generally accepted standard procedures are not defined The latter case is true for shear-modulus measurements, for example.

The Researchers

A large portion of the research efforts in Task 1 was devoted to analyzing previous experimental and theoretical research efforts related to elastomeric-bearing behavior.

The review of previous experimental efforts revealed that static and dynamic loads have been applied to bearings to observe the effects of these loads on compressive deflection, shear deflection, creep, and wear behavior. The bearings involved have been bonded and unbonded single pads, as well as molded and built-up laminated assemblies. Various elastomeric materials, as well as a wide range of nominal environmental temperatures, have been used. Bearing performance also has been investigated with a variety of materials in contact with the bearing surfaces, including concrete and steel.

Almost without exception, the bearings tested have been full size, their geometries have been described in reports by the shape factor term, sometimes to the exclusion of the actual dimensions of the elastomeric pads used. The materials investigated have almost always been described in the reports only by naming the base polymer and the associated Shore A durometer hardness (and perhaps the degree of conformity of the material to the AASHO or equivalent specifications).

It is difficult, in general, to correlate much of the data from these research efforts. For example, two sets of data for 60 hard, neoprene, bonded single pads with shape factor 4 give significantly different compressive load-deflection curves. For a given compressive stress, the absolute compressive-strain difference is about 5 percent. Inasmuch as present AASHO design specifications recommend limiting the compressive strain to 7 percent under dead and live loads, such data differences cannot be ignored if one is to use such data as indicative of bearing behavior. The difference in the data could be due to several factors, but, because of the lack of certain information attending the presentation of the data, the reason for the differences cannot be determined. The major factors that may have caused such a difference are creep and different shear moduli—even though the hardness values were the same. One should not necessarily assume that a hardness value is a good measure of shear modulus, even in a relative way. First of all, as is generally known, a hardness measurement is not highly accurate. A 60 hard material must be considered as 60 ±5 hard—a situation that could mean a sufficient variation in the shear modulus to account for some test-data differences. Secondly, a hardness measurement, which by its nature is a surface interaction, may not necessarily be indicative of the bulk-averaged properties of the material. The bulk-averaged shear modulus may be significantly different from the shear modulus at or near the surface; this occurs because it is not always possible to obtain the same degree of cure throughout the volume during vulcanization.

It is well known in the rubber industry that the shear modulus is different for different rates of load application. Although the experimental efforts that have included shear tests have recognized this fact, they have not always presented data for more than one shear-loading rate, making it impossible to determine the effects of loading rate in some *quantitative* manner. Thus, in trying to correlate various shear-test data, one cannot be sure that test differences are due only to load-rate difference, because a possible variation of shear-modulus value within a stated Shore A hardness is also present.

A particularly confusing situation exists within the state of the art with regard to creep, stress relaxation, and the effects of cyclic (dynamic) loads on elastomeric bridge bearings. Creep is the name normally given to continued deformation under constant load, and stress relaxation is the term applied to the situation in which a decreasing load is required to maintain the same amount of deformation. Both of these terms should be regarded as different behavioral aspects of one characteristic of the material—its internal structural response to loads. If one mentally relates creep, stress relaxation, and dynamic-load effects to the internal structural behavior, the effects of these three conditions on bearing behavior is clarified

It is pertinent at this point, then, to discuss the internal structural response of rubber to external loads. Basically, the internal structure is composed of long molecular chains which, in an unloaded condition, are oriented much like a pile of spaghetti. In addition to the end-to-end connections of the various structural units that constitute the chain, there are cross connections among chains that occur in no particular pattern or orientation. When a piece of rubber is put in tension, these chains tend to straighten out. But because the chains are oriented in all directions when the load is applied, some chains will straighten out more than others. The cross links among chains further tend to inhibit the straightening of chains. Thus, for a given load, some chains and cross links are highly stressed, whereas others are very lightly stressed. When fillers, etc., are included in this picture, the situation may be viewed as one in which materials that are intermixed with the chains and cross links inhibit the straightening tendency even further. This occurs because some of the filler particles are in the way and because other particles may themselves act as cross links. Thus, as the load is increased further, those highly stressed chains or cross links may break, shifting part of the load to other less highly stressed chains and cross links. If the load is now removed, the stretched chains and links will tend to return to their initially unloaded configuration. But the chains or cross links that have been broken cannot return to their original orientation. The result is that the piece of rubber will not return completely to its original dimensions after being unloaded. A similar situation occurs under compressive loads and results in compressive set.

Now, if a piece of rubber is loaded by applying either a fixed external load or a fixed external deformation, the internal structure is again loaded to different degrees in different locations. If the load is held constant in time, an internal redistribution of strain will occur; this occurs because some chains and links break, or because the filler molecules are moved around in such a way that they reduce the degree to which the chains and links are stretched. This internal redistribution will reduce the energy stored in the stretched chains and cross links to the point at which no further redistribution will occur. The outward manifestation of this internal redistribution is either creep under fixed load or stress relaxation under fixed deformation The internal redistribution can be speeded up by heating the material directly or by heating it indirectly by applying a cyclic load.

Now, discussion turns back to the behavior of elastomeric bridge bearings. Under a fixed compressive load (the dead load of the bridge), the vertical deformation will continue to some point. This creep never really stops; but, at some point, the additional deformation becomes negligible. Furthermore, the vertical live loads will increase the rate of creep and may even increase the "final" amount of deformation. This behavior, of course, affects the "final" elevation of the bridge.

Another important aspect of this creep phenomenon is that, with continued internal redistribution and settling of the bearing, the unloaded surfaces will be stressed in tension more and more, until the material develops a visual crack. Of course, a crack could appear on initial loading of the bearing. In this case, under creep, the crack could be elongated and widened with time. Any mechanism that speeds up this internal redistribution could be expected to cause cracking sooner.

In a bridge bearing application, one other factor influences the vertical creep-dynamic, horizontal shear loads. Their influence, as stated previously, is to hasten the internal redistribution phenomenon. These horizontal dynamic loads, in general, include the expansion and contraction of the bridge. But the rate at which this expansion and contraction occurs in practice is relatively low compared to the live vertical loads; it does not seem at all reasonable to expect this motion to have much of an effect on the vertical creep of the bearings or on the potential development of cracks.

A number of experimental programs have examined the effects of cyclic shear deformation on bridge-bearing behavior under compressive loads. In some cases, the fully reversed shear-deformation cycles (that is ±50 percent shear) were induced at rates up to 120 cycles per minute, and the tests were continued until several thousand cycles were accumulated. With such rates, significant bearing-temperature increases were observed. At the end of such tests, the physically observable characteristics (tears, abrasions, and cracks) were interpreted as indications of the durability of the bearings and the material.

It is submitted that the results of tests that apply ±50 percent cyclic shear-strain loads at rates on the order of tens or hundreds of cycles per minute must be very carefully interpreted. First, such shear-load rates are far in excess of what occurs in practice. Second, if creep is being investigated under such conditions, the effects of temperature increases (currently unknown) due to the high cycle rate must be considered. Finally, because the shear modulus increases as the load-application rate increases, the potential exists for inducing shear stresses far beyond those encountered in normal service. Such increased shear stress could be the cause of material cracks. In support of such tests, the usual argument, implicit or explicit, is that these tests really show what a material can do. On the other hand, because of the problems mentioned, such tests should not *necessarily* be considered valid as *material selection tests,* the tests are much too severe.

EXPERIMENTAL FINDINGS

The experiments conducted during this research program were as follows:

Group A: Shear Modulus and Stress Relaxation.
  1. Stress-strain in shear.
  2. Low-temperature effects.
  3. Shear stress relaxation under constant shear strain.

Group B: Compression and Rotation-Geometry Effects.
  1. Stress-strain in compression.
  2. Effects of shape factor and lamination.

Group E: Commercial Elastomeric Bridge Bearings.
  1. Stress-strain in shear.
  2. Stress-strain in compression.

Group F: Reversed Cyclic Shear.
  1. Shear modulus.
  2. Compressive creep.

To evaluate the effect of the hardness of an elastomer on the material property, shear modulus (G), all of the data from Groups A, E, and F were plotted. Despite a fairly wide spread in data points, it was possible to draw a smooth curve through these points; this curve is shown in Figure 1. The trend toward higher values of modulus for higher hardness readings was expected. It is interesting to note, however, that this curve is substantially "softer" than the values given in both du Pont's literature (*1*) and literature (*2*) of the National Rubber Producers' Research Association (NRPRA). Although this may reflect a built-in "safety factor" on the part of material suppliers, it does suggest that for the methods used in this research for evaluating the room temperature shear modulus of an elastomer, the load relaxation rate in shear is high enough in the higher hardness material to result in this less severely sloped curve.

The effects of temperature on the shear modulus of neoprene are best described as a stiffening at lower temperatures. The effect is not linear, however, and consequently the modulus increase with decreased temperature is expressed as a ratio of the modulus at the desired temperature compared to the shear modulus of the same material at room temperature, as given in Table 2.

Several points must be made in regard to Table 2. The effect of rapid crystallization is believed to have resulted in abnormally high ratios for the neoprene-dacron combination; compounding of the elastomer for low-temperature resistance might have alleviated this effect. It appears that compounding for a specific desired behavior is the key to the modulus results. Note that decreased temperature affects the 50-durometer neoprene much less than it does the harder compounds Note also that the du Pont predictions are not too far from the actual results.

The variation of stress relaxation in shear, expressed as a percent stress decrease per decade of time, is not a simple function but rather a general trend, as evidenced by the spread of data points from the Group A experiments. As the band in Figure 2 shows, greater stress relaxation is experienced at higher values of shear moduli, and, therefore, also at lower temperatures (the higher shear moduli were those obtained at lower temperatures). It must be pointed out, however, that the stress relaxation at lower temperatures represents only initial rates and may not be quite so high for long periods of time.

Perhaps one of the least understood properties of elastomeric bearing materials, especially from a quantitative standpoint, is the phenomenon known as crystallization. This is a tendency for the elastomer to gradually stiffen or harden under strain. In shear, this manifests itself as a noticeable increase in shear modulus over a period of time. In the Group A tests, after the period of stress relaxation under constant shear strain of 50 percent, a final shear cycle was accomplished in an effort to look for the effects of crystallization. The results are expressed in Figure 3 as a percentage increase in shear modulus with time at constant temperature. It appears that, inasmuch as the base polymer (neoprene) was the same for all four materials, the compounding of the material has a major effect on the *rate* of crystallization. It is significant that all neoprenes crystallized at their maximum rate at or near —20 F. Also significant is that the maximum increase in shear modulus after approximately 6 hr was as follows: 50-durometer, 75 percent; 60-durometer, 150 percent; 70-durometer, 125 percent; 57-durometer (neoprene-dacron), 250 percent. Therefore, it must be concluded that the compounding ingredients determine crystallization effects rather than the durometer hardness per se.

By definition, shear modulus (G) is a material property unaffected by considerations of size and shape. However, inasmuch as the modulus as used in bearing design to predict shear loads under strain might indeed be affected by geometry, data from Groups A and F were used to investigate this possibility. With the value of average shear modulus at a shape factor of 2.0 arbitrarily considered as unity, the calculated value of shear modulus of comparable materials varied a maximum of only 16 percent and no trend was discernible. In addition to shape factor, geometric parameters investigated included length-to-width ratio (b/a), width-to-thickness ratio (a/t), and sheared area. Of course, for very tall bearings a degree of bending must be accounted for in the calculation of shear

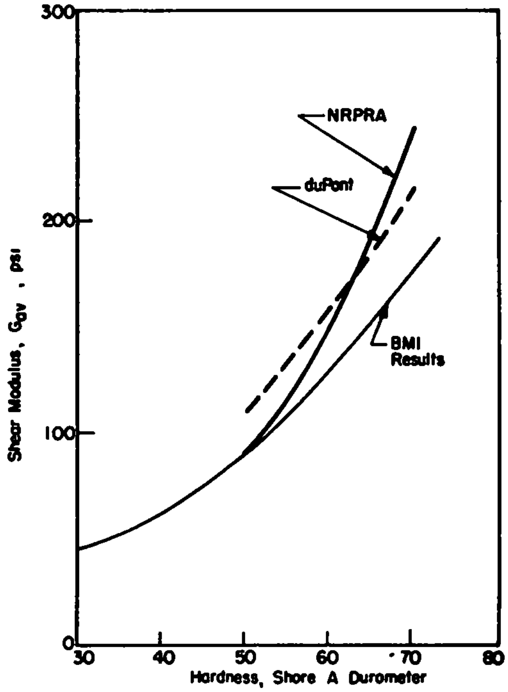

Figure 1. Shear modulus versus hardness.

TABLE 2

RATIO OF LOW-TEMPERATURE TO ROOM-TEMPERATURE SHEAR MODULUS

HARDNESS AND MATERIAL	RATIO FOR TEMPERATURE OF:				
	40 F	20 F	0 F	—20 F	—40 F
50-durometer neoprene	1.00	1.00	1.10	1.25	1.55
60-durometer neoprene	1.05	1.25	1.65	1.90	2.05
70-durometer neoprene	1.05	1.15	1.50	1.85	2.15
57-durometer neoprene-dacron	1.15	1.30	2.20	2.70	3.50
50- to 70-durometer neoprene [a]	—	1.10	1.25	1.95	—

[a] Du Pont (*1*).

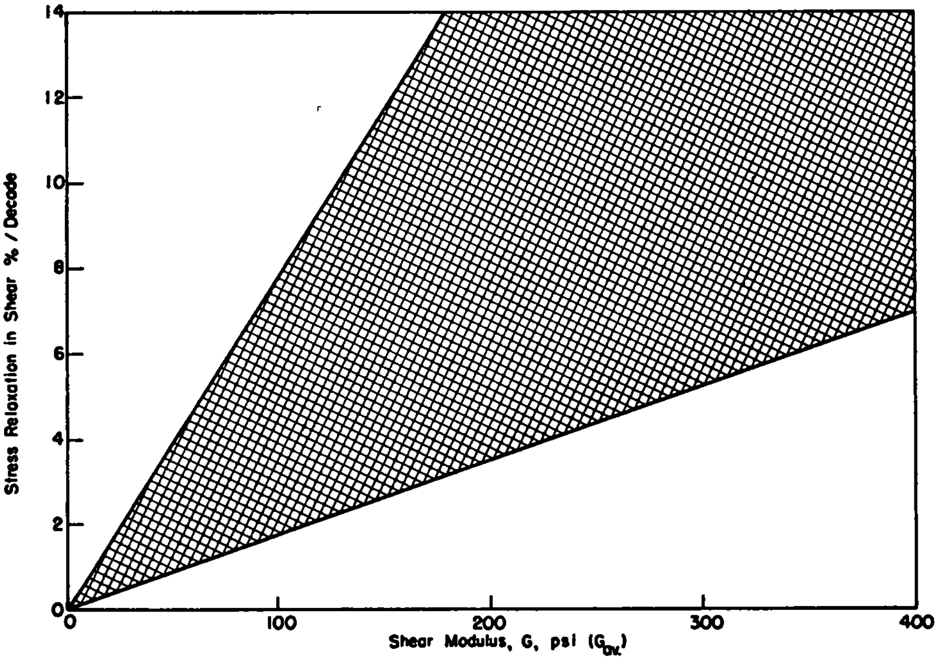

Figure 2. Stress relaxation versus shear modulus.

modulus, but this can be accomplished without difficulty [Lindley (*3*)], based on the length-to-thickness ratio (*b*/*t*). The conclusion is then that size and shape do not affect the shear modulus of an elastomeric bearing to any significant degree.

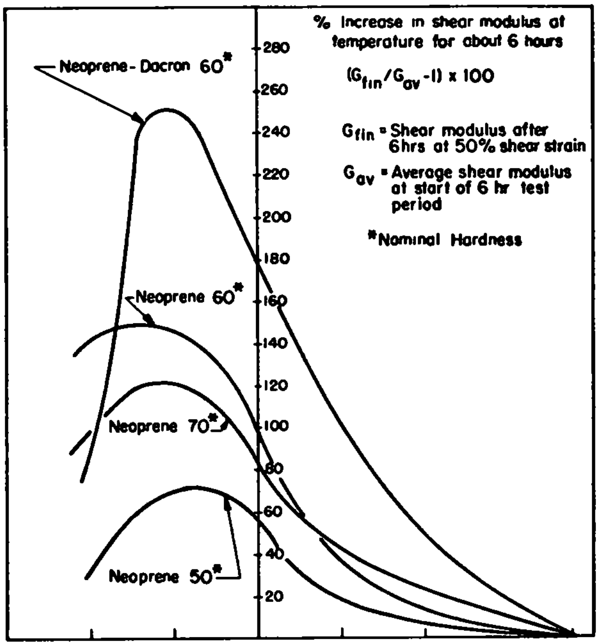

Figure 3. Increase in shear modulus with time at constant temperature.

One of the most important aspects of the behavior of bonded elastomeric bearings is the relationship between the bearing shape and the compressive stress-strain results. For this reason, a major part of the experimental program was devoted to this area and a substantial amount of data was developed in Groups B and F. It was found during analysis that a reasonably good fit of the data could be realized by assuming an equation of the form:

$$\epsilon_c = a\,S^b \tag{1}$$

in which:

ϵ_c = compressive strain, percent;
a = compressive strain at a shape factor of 1 percent;
S = shape factor = one loaded area/total free area; and
b = empirically derived constant.

Although the data spread about this curve is large, this is judged to be due to experimental error and therefore would not affect the engineering approximations gained by using Eq. 1. (Experimental error in this case includes not only variations due to testing techniques, but also modulus (hardness) variations from sample to sample and within each sample.) For a range of shape factors from about 1 to 20, Table 3 gives the values of "*a*" and "*b*" for use with the foregoing compressive behavior equation. For intermediate values of hardness or compressive stress, interpolation is adequate for most engineering purposes. In a more tractable form, however, this information may be presented in the traditional manner as curves of compressive stress versus strain, each curve representing one value of shape factor, with a separate plot for each hardness. This is done as shown in Figures B-19, B-20, and B-21.

An interesting finding during analysis of the compressive

TABLE 3

CONSTANTS FOR SHAPE FACTOR PREDICTION OF COMPRESSIVE STRAIN

HARDNESS	COMPRESSIVE STRESS, σ_c (PSI)	a (%)	b
50-durometer	500	27.77	−1.050
	1,000	32.91	−0.805
	1,500	38.06	−0.727
	2,000	48.37	−0.798
70-durometer	500	21.55	−1.051
	1,000	30.74	−0.964
	1,500	31.69	−0.835
	2,000	32.30	−0.719
57-durometer [a]	500	25.73	−0.923
	1,000	32.27	−0.699
	1,500	25.59	−0.423
	2,000	26.58	−0.377

[a] Neoprene-dacron, unbonded

behavior from Groups B, E, and F was that the stress-strain results deviated significantly from that predicted by both the theoretical (*4, 5*) and the empirical or shape factor (*2*) approaches. Basically, for low values of shape factor (1 to 4) the theoretical approach seemed most valid, although this approach always predicted a stiffer bearing than was actually the case. For intermediate values of shape factor (3 to 5), the empirically derived approach using the shape factor as the sole geometric parameter appears to agree most closely with the experimental results. However, for values of shape factor higher than 5, neither approach gave satisfactory predictions of compressive stress-strain behavior. For high shape factor bearings, then, more compressive deflection is experienced than that expected either theoretically or from previously derived empirical relations.

The effects of lamination on the compressive behavior of bonded elastomeric bearings were not significant enough to be detected within the range of experimental error. It must be concluded, therefore, that, at least for engineering accuracy, the total compressive deflection under load for a laminated bearing may be calculated by multiplying the expected deflection for a single laminate by the total number of laminates In cases where the laminates vary in thickness (and consequently in shape factor), the deflections of the respective laminates may be added.

A special case in regard to the compressive deflection of laminated bearings is the behavior of neoprene-dacron combination bearings. It appears that whereas the dacron sheet is constrained where it contacts a steel or concrete surface, it is reasonably flexible when laminated (either bonded or placed together) as in the middle of a multilaminate bearing. This flexibility allows the central laminates to expand so that the deflection is not simply that of a single laminate multiplied by the number of laminates, but rather somewhat greater. In general, it can be tentatively stated qualitatively that for neoprene-dacron of constant shape factor, the greater the number of laminations, the greater the compressive strain

A small effort was made during the Group B tests to investigate the effects of holes on the compressive stress-strain behavior of bonded bearings Specifically, several bearings were tested with variously sized holes cut through them. It was found that a calculation of shape factor based on the reduced load area (length × width − hole area) divided by the increased free area [2(thickness)(length + width) + (thickness)(hole circumference)] allowed the data points to fall on the previously derived curve of shape factor versus compressive strain. Therefore, it is expected that compressive behavior can be related directly to shape factor as the most convenient method of predicting performance.

Group E experiments with commercial bearings attempted to evaluate the effect on the material property, shear modulus, of bonding and vulcanizing large bearing pads. There was some question that, although a hardness test on the surface of a commercial pad might indicate a certain value of shear modulus, the interior of the bearing might be substantially "softer" due to lessened effects of vulcanizing through the bulk. It was found, however, that no discernible variations in modulus occurred in the interior of bearings of the sizes and shapes examined.

The effect of shear cycling on the shear modulus of a bearing sample was evaluated in the Group F experiments. In all cases except two, the shear modulus decreased very gradually while 10^5 cycles between ±50 percent shear strain were accomplished; in two cases the shear modulus increased about 5 percent from 10^2 cycles to 10^5 cycles. For all other samples, the average decrease was on the order of 5 to 10 percent over the same number of cycles. This is in general agreement with the values for stress relaxation in shear from the Group A tests (see Fig 2).

The effect of shear cycling on the compressive strain, or compressive creep of a bearing, was also investigated in the Group F experiments. For slightly over 100,000 cycles, the compressive creep values ranged from 14 percent for one sample of 50-durometer natural rubber to 73 percent for a sample of 70-durometer neoprene. A large jump in initial creep value was noted when the shear cycling was first initiated, an indication that cycling increases the total creep exhibited by a bearing compared to that encountered with a static situation. Based on the curves of creep versus time, there seems to be no uniform effect of shape factor on compressive creep. As was expected for neoprene, the greater the modulus (hardness) the greater the creep; this is attributed to the amount of filler used in the original compounding. Comparing the four tested materials does not give conclusive evidence that one material has less creep than another. It is interesting to note, however, that the design information published by du Pont (*1*) gives substantially lower values of creep for short times than those resulting from the tests under reversed cyclic shear.

Some general statements are in order regarding the relative performance of glued (bonded) laminated pads compared to fully vulcanized units. During the entire experimental program, problems were encountered with pads prepared by bonding to steel plates with an adhesive. In some cases the adhesive did not adhere properly to the elastomer. In other cases the waviness of the steel surface left areas where the bond was not complete. With the fully vulcanized units, however, even when the pad had been cut through, the bond remained excellent under all conditions of shear and compression.

On the matter of cutting bearings from larger sheet stock, all test samples were prepared in this manner from ¼-, ½-, and 1-in. sheet. A single shear cut from a well-dressed steel blade produced a near-straight, smooth cut in all cases, without any taper or cupping due to elastomer compression. For the large commercial bearings laminated with steel plates, an abrasive grinding cut-off wheel was used, and whereas many short strokes and some time were necessary to complete the cut, the results were uniformly smooth surfaces and no deterioration of the elastomer. The fact that none of the bonds was affected by this method is evidence that the edge of the abrasive was actually cutting, rather than "plowing," through the elastomer. Coolant was used to reduce heating when the abrasive wheel passed through the steel.

Of interest in the design of bearings to accommodate large shear deflections was the observation of instability under compression in two laminated bearing samples during Group B tests. Both bearings had a shape factor of 4.0. A nine-laminate bearing became unstable at about 1,400 psi average compression, whereas an 18-laminate bearing became unstable at 600 psi.

CHAPTER THREE

APPRAISAL AND APPLICATION OF RESEARCH FINDINGS

APPRAISAL

Any appraisal of the findings in Chapter Two must begin with a critical evaluation of the data obtained during the experimental plan of the program. This is, in short, an estimate of the reliability of the data, and hence the findings. A general statement covering the entire program is that a great amount of material properties and design information on elastomeric bridge bearings was attempted with a minimum number of tests. Exclusive of experimental scatter, then, the degree of confidence in the findings is limited by the fact that an in-depth study of parameters affecting bearing behavior and performance was not made, but rather a short look was taken into several areas. The result furthers understanding of which areas have a greater importance (or priority) in both design and performance of bonded elastomeric bridge bearings.

The experimental phase was planned to develop information on the properties of the candidate bearing materials and also shape-related effects on bearing behavior. Group A tests on shear modulus and stress relaxation, both material properties, are viewed as generally valid. Experimental error was reduced to a minimum by carefully measuring all physical quantities. The possible exception is the maintenance of constant temperature and isolation of the material from crystallization effects. The former assumed that the sample would reach a steady-state temperature condition in about 1 hr at constant low temperature, whereas the latter assumed that crystallization would be negligible in the same time period.

Group B tests investigating geometry effects, as indicated by the data spread, appeared most affected by experimental scatter. Performance evaluations under initial compression of bearings of various sizes and shapes has in the past been limited to bearings of low to medium shape factor (up to about 6). Therefore, the data and the approximate curve-fit at least extend knowledge of this performance into the range of higher shape factors (up to about 14). An indication of the validity of this approximate prediction is its relatively good agreement with the data for compressive strain at low shape factors. Probably the biggest source of deviation in these experiments (and possibly in actual bearing performance as well) is the variation in material properties. Although hardness values are recognized to be only an indication of the shear modulus of an elastomer, it should be noted that at a value of 50-durometer (50 ±5) the variation in modulus can be as much as 40 percent (see Fig. 1). The other alternative to hardness readings, direct measurement of each sample in shear, was not feasible due to the range of sizes and shapes.

The commercial bearings tested in Group E under shear and compression were of known geometry and hardness. The test conditions were similar enough in these two loading modes to be compared to the first two groups. The largest scatter must therefore be attributed to variations in material properties and the possible effect of parameters considered not significant, such as size and lamination effects on the shear modulus. That the compressive behavior of the bonded steel-laminated bearings agrees reasonably well with that predicted by the data curves from Group B suggests that the results from these bearings are valid.

Group F tests covering cyclic shear under constant compression were, if anything, too short and too few to generate valid data on fatigue or bond deterioration or compressive creep. Additionally, the cyclic rate used during the testing constituted an invalid approximation of actual bearing behavior, even though it was necessary from the standpoint of conducting the tests in a reasonable length of time.

An evaluation of the over-all experimental phase, then, would be that from the engineering and design point of view the most valid results are those dealing with the material property, shear modulus (only of the compounds tested), and the effects of shape factor on compressive stress-strain. From the point of view of more exact results in a research sense, too little data were derived to statistically validate any of the many parametric variations investigated.

INTERPRETATION AND APPLICATION

The results of this research may be applied in several ways to the general area of elastomeric bridge bearing design methodology. The behavior of bonded elastomeric bearings is characterized by the three specific loading modes of shear, compression, and rotation. Although the rotational aspects of bearing behavior were not evaluated during this research, the findings in Chapter Two may be applied to the design methodology for both shear and compression loading.

Perhaps the most important and valid findings as a result of the experimental phase are the curves of initial compressive stress-strain behavior as affected by both hardness (or shear modulus) and shape factor. Most design information in the past has been limited to shape factors below 4, so these research findings may be applied for engineering purposes to bearing designs using higher, and from a performance standpoint generally more desirable, shape factors. Although a limit on compressive stress of 800 psi may be arbitrary, it is a convenient reference point from which to begin the design; knowing the loading, a compressive bearing area may be determined. An arbitrary ratio of length-to-width of about two is a sufficient first trial value. It is important here to make absolutely certain that the length of the bearing is less than the width of either the supporting abutment or pier seat and also the supported bridge beam. To determine the first approximation of bearing thickness, both a material hardness and a shape factor must now be chosen. Having selected the hardness (and thus the shear modulus), one can find a shape factor from the curves that will result in the desired initial compressive strain. This is limited to 7 percent by the AASHO specifications. On the matter of compressive creep, du Pont data suggest that the major portion of this creep is likely to occur during the first month after installation, probably less than the time between placement of the bearings and actual use of the bridge. Within engineering accuracy, this creep can be predicted ahead of time and designed for, so that the bridge deck and roadway heights are substantially level in service. Creep is not a factor in the design of bearings to be placed under continuous spans. It is important, though, that creep characteristics under constant load be known ahead of time. That concludes the design of the bearing in compression, and leads directly into considerations of shear behavior.

The limitation on shear strain to 50 percent of the bearing effective (total elastomer) thickness is also a design guide. Knowing the expected bridge beam expansion and contraction due to temperature change, one should design the total bearing thickness to be at least twice this movement. This thickness requirement generally dictates a multilaminate configuration, with each laminate having the dimensions necessary to keep the shape factor at the value calculated from compression considerations. It is important here to check for vertical instability by applying the limitations found in the AASHO specifications: the bearing length must be at least three times the total elastomer thickness, and the bearing width must be twice this thickness. Possibly the most critical loading behavior must now be analyzed—the shear loading expected from the movement of the bridge spans. A "worst case" condition must be selected, and herein lies the difficulty. The shear load is the product of the maximum shear strain (50 percent), the bearing area (length × width), and the shear modulus. The first two quantities are known, but the shear modulus and stress relaxation (which may be viewed as a reduction in modulus with time) under all conceivable service conditions are not. And the worst case probably can be defined as a shear movement of the bridge beam after the bearing has been held at its maximum rate of crystallization temperature for some time. If the environmental conditions never include situations where crystallization can be significant, then the shear modulus is merely a function of temperature. Also, if one is dealing with a noncrystallizable material (as some synthetics are reported to be) then shear modulus again is just a function of temperature. But the results of this research show that even for as short a time as 5 hr, a substantial modulus increase can be expected in quite a wide range of temperatures for the materials studied. Quantitative data and design information on this phenomenon are unfortunately almost nonexistent, so any predictions of shear behavior at low temperatures over long periods of time must be largely speculative in nature. It might be noted at this point that inasmuch as stress relaxation in shear seems to be generally proportional to shear modulus, the greatest relaxation should occur at the highest shear strains and when the effect of crystallization is most severe. This is true; however, the rate of stress relaxation is too low to allow more than a small margin of safety to the loading expected from elastomer stiffening at low temperatures.

In summary, then, application of the research results should lead to a better understanding of the importance of various design parameters, particularly in the area of shape-related behavior. The exception is rotational behavior, where more work is necessary. Material properties as related to elastomeric bridge bearing performance are now more clearly defined, so that design and specification may accommodate the important material-related parameters.

CHAPTER FOUR

CONCLUSIONS AND SUGGESTED RESEARCH

CONCLUSIONS

The general conclusion that may be made as a result of this research program is that there is now a better understanding, both quantitatively and qualitatively, of the major factors that influence the design and performance of elastomeric bridge bearings. It has been learned that the best approach to defining bearing behavior is first to gain information on elastomeric material properties of importance, and then to combine this information with geometric, or shape-related, parameters. Concurrent with the better understanding of bridge bearing performance is the realization that far more work is necessary to develop specific quantitative materials data and to refine shape-related parametric evaluations.

As might be expected in a relatively new use of an elastomeric material, it is the major bearing manufacturers and also the material suppliers who have had the greatest experience with actual bridge bearing performance. For this reason it can be stated that, in an engineering sense, currently available commercial bearing designs often behave as predicted. Even so, it is recommended that, if at all possible, both shear and compression tests to verify predicted stress-strain performance be carried out on representative bearings for a given installation. This is necessary not only for quality assurance considerations, but also to ensure that actual loadings will be within specific bridge design safety limits In this regard and in light of the relative lack of information about time-dependent low-temperature material properties, it is strongly advised that a large safety factor be applied to the expected shear loads during the bridge design phase. This may be done by strengthening the supporting and supported structures, and by ensuring that the bearing is maintained in its position with a cast-in seat, or preferably by structural pinning. Another method might be to design the elastomeric bearing for less than 50 percent shear strain to limit the loading. The expected bridge beam bending should not be overlooked, and the bearing can be topped with a tapered plate to match the beam bending (rotation angle) at halfway between dead load and dead plus live load.

In the light of the findings in Chapter Two of this report, the sections in the AASHO specifications covering elastomeric bearings (Sections 12 and 25) may be appropriately modified to reflect desired performance as well as material quality. In the area of bearing designs, defined by Section 12, the current concept of shape factor should be retained as the most convenient method of defining bearing geometry. The findings of the research agree with the statement that, for bonded laminated bearings, the compressive deflection may be found by multiplying the deflection of a single laminate by the total number of laminates. The two occurrences of instability under compression during the Group B tests tend to support the limitations of minimum length to $3T$ ($T =$ total elastomer thickness) and minimum width to $2T$. Limiting the total movements in shear to $0.5T$ seems valid, if only to avoid excessive tensile stresses in area of the bond edge. No data were developed during the experiments that would seem to justify a limitation on compression stress to 800 psi for dead plus live load and 500 psi for dead load, at least from the standpoint of material failure. This appears to be an arbitrary restriction imposed for one of two reasons. Either compressive creep under higher average compressions is believed to be too high (an area not fully investigated by this research), or the localized maximum concrete seating surface stresses are exceeded by higher average bearing stresses It is interesting to note that the average compressive stress limitation of 800 psi, combined with the initial compressive strain limitation of 7 percent, dictates a bearing of shape factor greater than 6 for 50-durometer material and greater than 4 for 70-durometer material.

In the area of bearing materials, defined by Section 25 of the AASHO specification, several comments may be made. First, there has been no indication in the studies made to date that cracking of elastomeric bearings due to ozone attack is anything more than a surface effect. For this reason, the test for these effects is considered unnecessary. All other tests are probably necessary to evaluate the quality of the candidate material, but such properties as compression set, heat resistance, and low-temperature behavior come close to defining performance under actual bridge conditions. In particular, the low-temperature test would seem to be almost meaningless unless the bearing material is compounded in such a way that the temperatures at which the maximum rate of crystallization occurs is —20 F (as it was for the neoprenes tested in Group A). Far more should be known about the crystallization phenomenon before a meaningful test or tests can be included in the specifications. From the findings dealing with neoprene during this program it can be seen that of the available hardnesses, the lowest value, 50-durometer, is probably the best for two reasons. As expected, compressive creep is less for 50-durometer elastomer than for either 60- or 70-durometer, probably because creep is related to the amount of filler material used in the compounding, and the higher the hardness, the more filler has been added. And it appears that (for the elastomer compounds investigated) the 50-durometer material also is affected least by crystallization at low temperatures under strain. In this regard, if further research should prove that the lower-durometer elastomers exhibit the best material-related qualities, then perhaps only these low-hardness materials should be specified. These qualities should be minimum long-term compressive creep, minimum hardness increase with decreasing temperature, maximum resistance to crystallization at all operating temperatures, and maximum rates of stress relaxation under shear strain. With the possible exception of the stress relaxation, all these qualities were found in the 50-durometer material investigated by this research. In the long run, it should be possible to specify for each base polymer a "best" bridge bearing elastomer, including the exact proportions of compounding ingredients, together with the processing procedure. In this way, standard bridge bearing materials would be available, compounded to meet specific performance characteristics, and these characteristics would be available to the bridge engineer as design information. As a major conclusion to this research, it should be obvious that hardness should be replaced by shear modulus as the basic material parameter necessary for the clear understanding of elastomeric bridge bearing behavior in service.

SUGGESTED RESEARCH

Some general comments are in order regarding the value of continuing research in the area of elastomeric bridge bearings. First, the experience with these bearings in the United States may be described as mixed; there have been numerous successful installations, and several notable failures. The latter have been due to inadequate designs, erroneous installation practices, or a general lack of understanding of those parameters that most affect elastomeric bridge bearing performance. Nevertheless, the increasingly successful application of empirically derived technology is resulting in increased numbers of bearing installations. The reasons are fairly well known.

1. Initial cost for elastomeric bearings is much lower than the cost of mechanical rocker devices.
2. Installation is generally easier and, hence, less expensive.
3 Maintenance is reduced essentially to zero.

This last item may be compared with mechanical devices that must be cleaned and painted annually to prevent "freezing" due to corrosion, and the consequent frequent failure of the devices to provide for bridge beam movement Therefore, research into several areas of elastomeric bearing behavior is warranted.

There is every indication, both from the results of this research and from experience in the field, that one of the least understood elastomeric material properties is the crystallization phenomenon. This is characterized by an increase in hardness, or modulus, of the elastomer under strain and is both time- and temperature-dependent. Further, for a given compound there is a specific temperature at which the rate of crystallization is a maximum. The rate also appears to be time-dependent in that the crystallization process at a specific constant temperature occurs very slowly at first, then accelerates to a maximum, and finally tapers off when the amount of crystallization nears its limit. And that final limit is also a characteristic of the specific elastomer compound. It is recommended that a thorough and exhaustive study be made of this phenomenon, initially on the AASHO-approved materials of neoprene and natural rubber, making certain that the compounds and vulcanization techniques are comparable to those used for actual bridge bearing materials. A standard shear test should be used; tests on samples held at constant temperatures for various lengths of times and then sheared would result in the data necessary for the proper design of bearings for optimum performance, without jeopardizing the success of the installation. Once the effects of crystallization are understood, the AASHO specifications for each material might include a standard test taken at the temperature of the maximum rate of crystallization and at one temperature higher and one lower.

The investigation into the crystallization phenomenon should be a first step toward an over-all evaluation of candidate bridge bearing elastomers. Although only two base polymers in three hardnesses are currently included in the AASHO specifications it is likely that other materials, if properly compounded, would be suitable for use in bonded elastomeric bridge bearings. For instance, the limited amount of experimental work with EPDM during this research indicated no serious shortcomings of this material. A laboratory evaluation would include temperature and time effects on shear modulus and stress relaxation, as well as compressive creep and elastomer fatigue under cyclic shear. If this information could be provided by material producers, a comparative evaluation would be relatively easy. But only through a completely impartial laboratory investigation using standard testing procedures can the required data be satisfactorily compared.

No laboratory evaluation of elastomeric material properties can stand by itself. A concurrent field evaluation is necessary to verify predicted performance. Several states have undertaken the monitoring of shear and compressive deflection in elastomeric bearing installations in an attempt to correlate design data with actual performance. This should be continued and the results should be combined systematically to note trends and early variations; this conceivably could be done through a central data-gathering body such as the Highway Research Board. Once the field performance data have been compared with engineering predictions, the design procedure for elastomeric bridge bearings may be updated and improved.

The results of this research have shown a very definite need for a statistical approach to the evaluation of shape-related effects on bridge bearing behavior. This is particularly true to determine the validity of current shape factor versus compressive stress-strain predictions. A single material and compounding should be chosen, together with a single elastomer thickness to assure that the material properties are constant within very small percentages. The material supplier could be asked to provide, say, a shear modulus (standard test method) of 100 psi in 0.5-in.-thick sheets. Initial laboratory tests run in shear not only would check that this modulus was constant, but also would provide a validation of the assumption that shear behavior is not shape-related. Standard compressive stress-strain tests would be next, preferably at the same loading rates as those used in this research so that the data could be correlated. Bonding must be excellent between the laminating plates and the elastomer surface; any bonding flaws will result in erroneous data. Sample dimensions must be carefully recorded. The experiments should be planned and the data should be analyzed not only with shape factor as a parameter but also with the ratios of length-to-width and width-to-thickness. The statistical nature of the data will provide a degree of confidence in the results that was not previously available. Two related areas might be covered in this testing: (1) compressive instability, and (2) rotational behavior. Instability may be investigated by bonding laminates of various-shaped bearings and compressing until instability occurs. This would provide quantitative design information that would allow more efficient use of bonded elastomeric bridge bearings in shear.

A final area for research should be a continuing effort to develop a viable theoretical formulation for the behavior of bearings in all modes of loading. The results of the research included in this report indicate that whereas the theoretical approach currently available is not adequate, the shape of the compressive stress-strain curves does agree far better with the theoretical than with the empirical predictions. The theoretical formulations thus developed by continued research should be capable of predicting stresses and strains in such a manner that design limits can be imposed on bridge bearings based on material allowables. The entire spectrum of bonded elastomeric bridge bearing behavior would thus be predicted theoretically and validated empirically.

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APPENDIX A

GROUP A—SHEAR MODULUS AND STRESS RELAXATION

The Group A experiments covered the effects of time, temperature, and previous history on the shear modulus (*G*) and the related stress relaxation of laboratory-size sample bearing pads. Included are the results of tests with 50- to 70-durometer natural rubber and EPDM at room temperature, and neoprene-dacron combination at temperatures between 75 F and −40 F. These experiments were carried out in an effort to obtain material properties data for use in the other experimental groups, as well as to investigate these properties from the standpoint of actual elastomeric bridge bearing use.

EQUIPMENT

The machine used in the Group A experiments was the Baldwin-Southwark hydraulic compression-tension test unit, used here in its compression mode. This machine has a maximum capacity of 20,000 lb. Coupled to this unit is (1) a direct readout of platen movement through a tape drive, and (2) a load/deflection recorder (pen on graph). This latter device records (1) the load through a mechanical-pneumatic hookup, and (2) the relative deflection of the moving platen to the fixed crosshead by a motor driven from the output of an LVDT (extensometer). As used in the Group A experiment, the recorder provides a permanent graph of shear load versus shear deflection.

Figure A-1 shows schematically the experimental rig designed around the Baldwin unit to accomplish the shear of elastomeric samples. Figure A-2 shows the set-up with a sample installed. The load cell is a BLH 20,000-lb-capacity unit mounted between the shear plate and the crosshead,

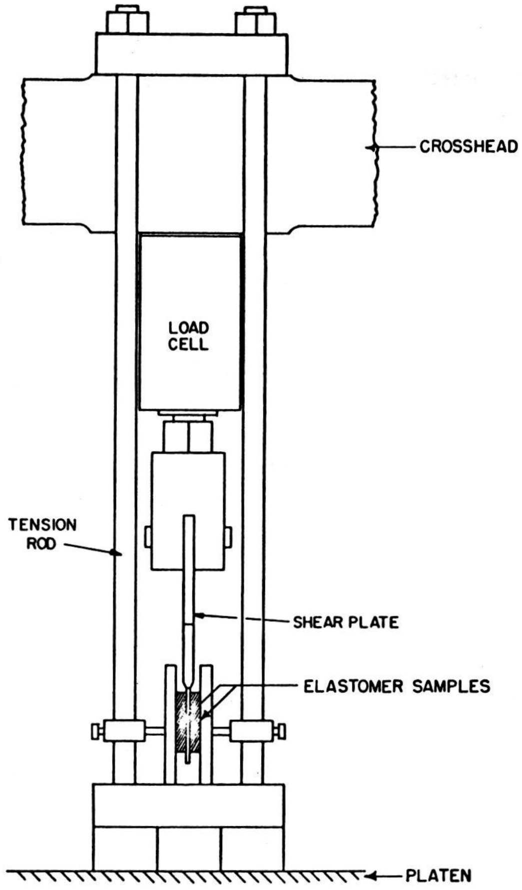


Figure A-1. Experimental set-up for shear and stress relaxation.

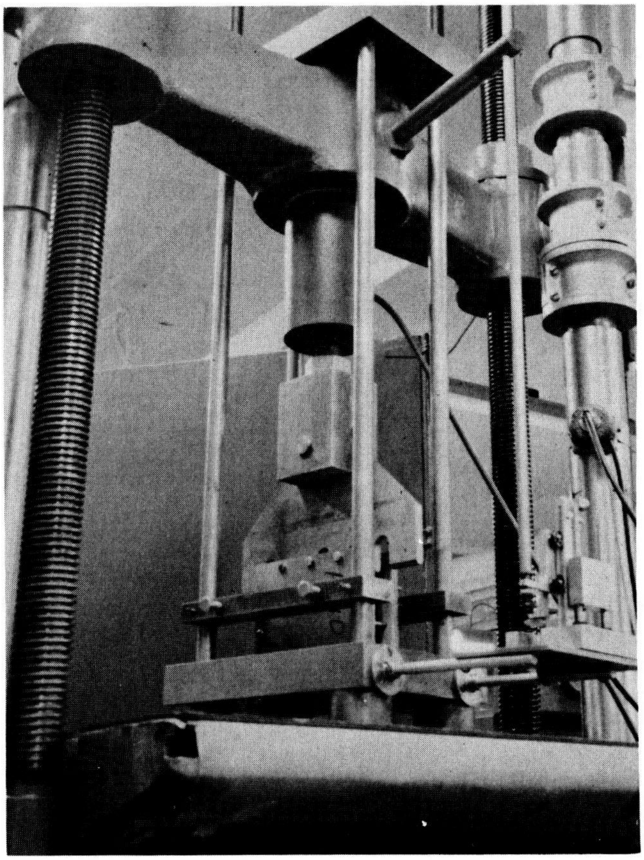


Figure A-2. Shear test set-up, containing sample.

and reads out through a BLH Type N SR4 strain indicator. The load cell was recalibrated before use in this investigation.

For the low-temperature work, a plywood "cold box" was constructed using ¾-in. plywood and lined inside with 2 in. of foamed polyurethane insulation. Cutouts were necessary through the box to allow for the shear plate, tension rods, and support feet. Figure A-3 shows schematically the control and monitoring of the temperature within the box. Figures A-4, A-5, A-6, and A-7 show various aspects of the cold-temperature set-up. Liquid nitrogen is fed under pressure to the cold box through an electromagnetic solenoid valve with a teflon seat. This valve is regulated (on/off) by a potentiometric unit that compares the potential across a copper-constantan thermocouple in the cold air beside the elastomeric sample (see Fig. A-6) to a voltage set manually in the unit. The electronic unit has an allowed variance of ±4 F. The other thermocouples are monitored selectively through a potentiometer and are placed as follows: #2, in the air on the other side of the elastomeric sample; #3, in the center of a 1-in. cube of neoprene with one side against the insulation; #4, in the center of a 1-in. cube of neoprene glued to the lower load plate. The temperature control of the cold box is thus automatic.

METHOD

Shear test samples were cut from the appropriate sheet stock with a single shear stroke from a pneumatically operated blade. The materials were neoprene, natural rubber, EPDM, and neoprene bonded to dacron. In almost every case, the blade left a straight smooth cut, even in the neoprene bonded to dacron; all sheet stock was ½ in. thick, in hardnesses from 50 to 70, as measured with a Shore A durometer. At the start of the investigation, bearing samples were bonded to the steel plates with an adhesive that required clamping and curing for some time at high temperature. It became obvious, through a noticeable reduction in hardness and shear modulus, that the natural rubber samples were affected by the heat, and a new bonding agent was selected that required only light pressure and room-temperature cure. The natural rubber bearings were then repeated and are noted by an "R" after the sample designation. The bonding method is found in Appendix E. The neoprene-dacron combination bearings are not bonded, but rather are placed between the steel plates. Length, width, thickness, and hardness of each sample were recorded. The data on these samples appear in Table A-1.

Each "sandwich" of two outer steel plates, two elastomer samples, and a central shear plate was bolted to approxi-

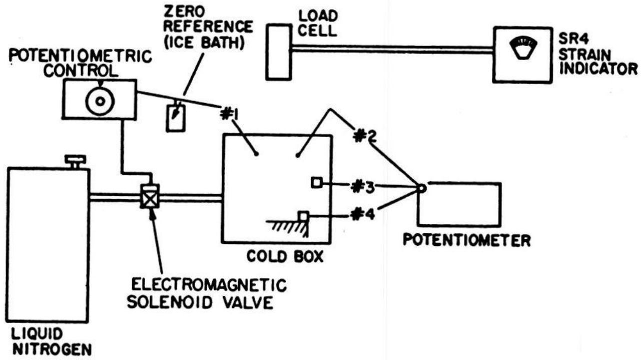


Figure A-3. Cold-temperature test set-up.

mately 10 percent compression immediately (5 min) before being placed in the rig for the shear test. The sample was then loaded at a constant and uniform rate of about 8 percent per minute to 50 percent shear strain, and was then unloaded to 0 percent shear strain at the same rate; the shear cycle was repeated four times to assure conditioning, and then a fifth loading was accomplished and the sample was held at 50 percent shear strain while the load was transferred from the platen to the tension rods by torquing the nuts down on the rods. This load transferral was accomplished in approximately 1 to 2 min. The "hold" time was recorded as the start of the stress relaxation phase; the load reading was taken from the SR4 strain indicator at roughly 2-min intervals for 10 min, then a reading was taken at half an hour, 1 hr, 3 hr, and 5 hr. For the room-temperature tests, the final reading was taken at about 22 hr. At the end of the stress relaxation phase the platen was again used to remove the load on the tension rods, the nuts were removed, and an unloading of the sample was accomplished. A final shear load-unload cycle to 50 percent shear strain completed the investigation.

At the start, an investigation was made of the effect of loading rate on shear modulus to determine the appropriate rate. The results of this showed that rates up to 40 percent shear strain per minute were in the "flat" region of the modulus-rate curve; i.e., a change in rate produced only a very slight change in modulus. However, as the trend was to increase the modulus with increased rate of loading, 8 percent shear strain per minute was selected. The modulus calculated at this rate was only about 1 percent higher than the modulus extrapolated at 0 percent shear strain per minute loading rate. Figure A-8 shows a representative load-deflection graph during investigation of a sample. The indexing was made on the recorder so as to avoid overlapping load-deflection plots. The indexing was performed

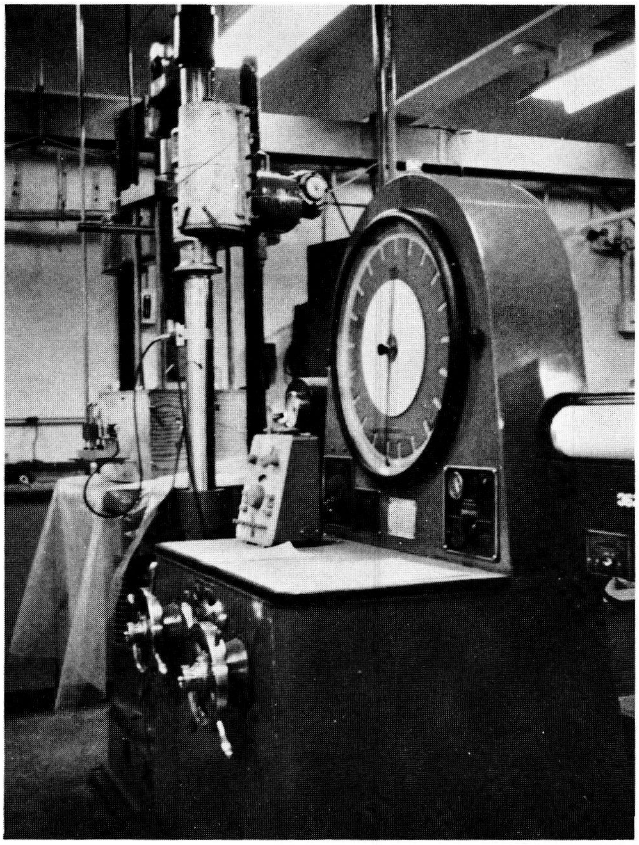


Figure A-4. Over-all view—low-temperature test set-up.

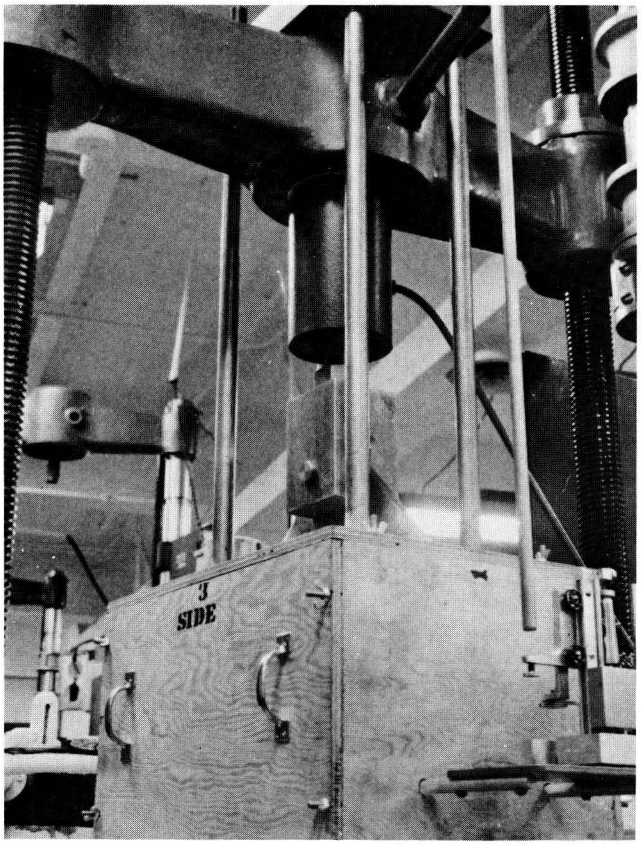


Figure A-5. Exterior of cold box.

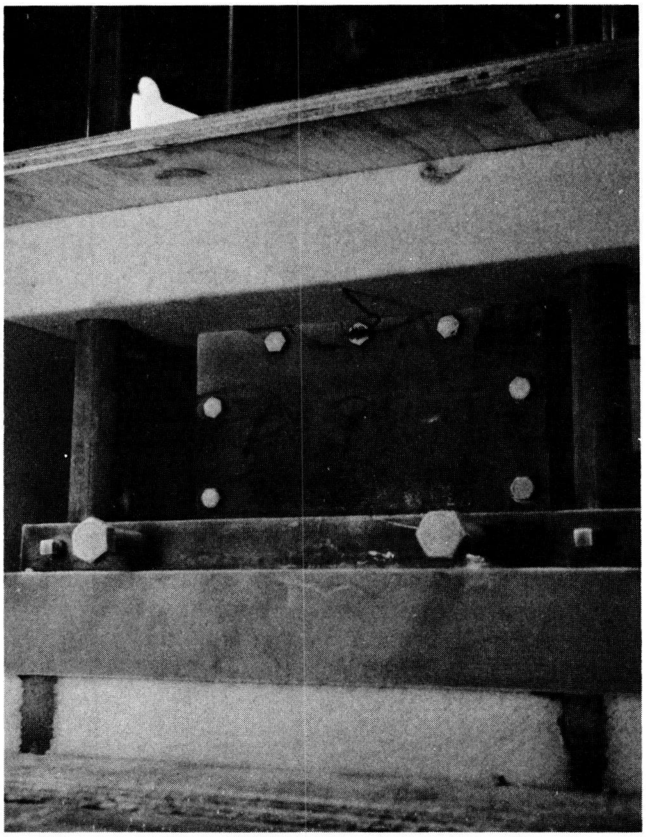


Figure A-6. Interior of cold box.

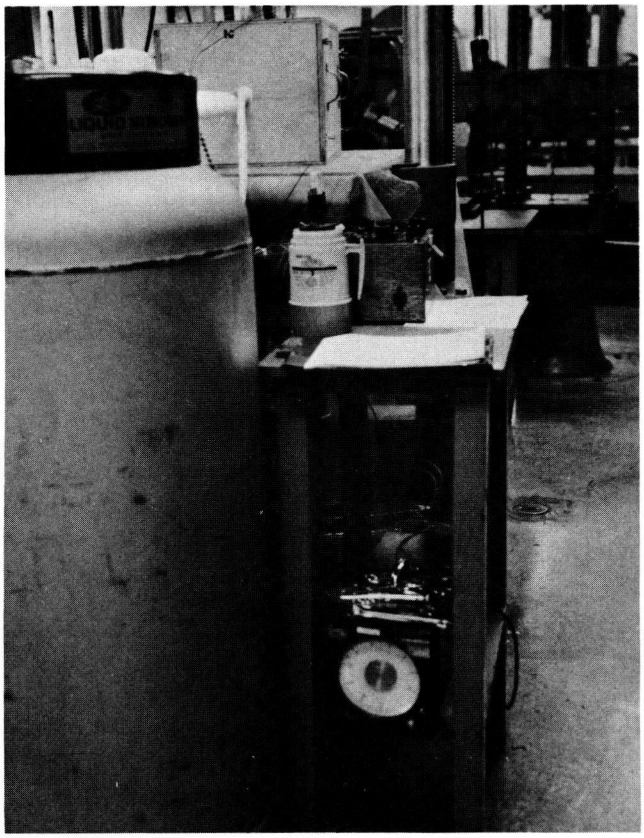


Figure A-7. Liquid nitrogen metering system.

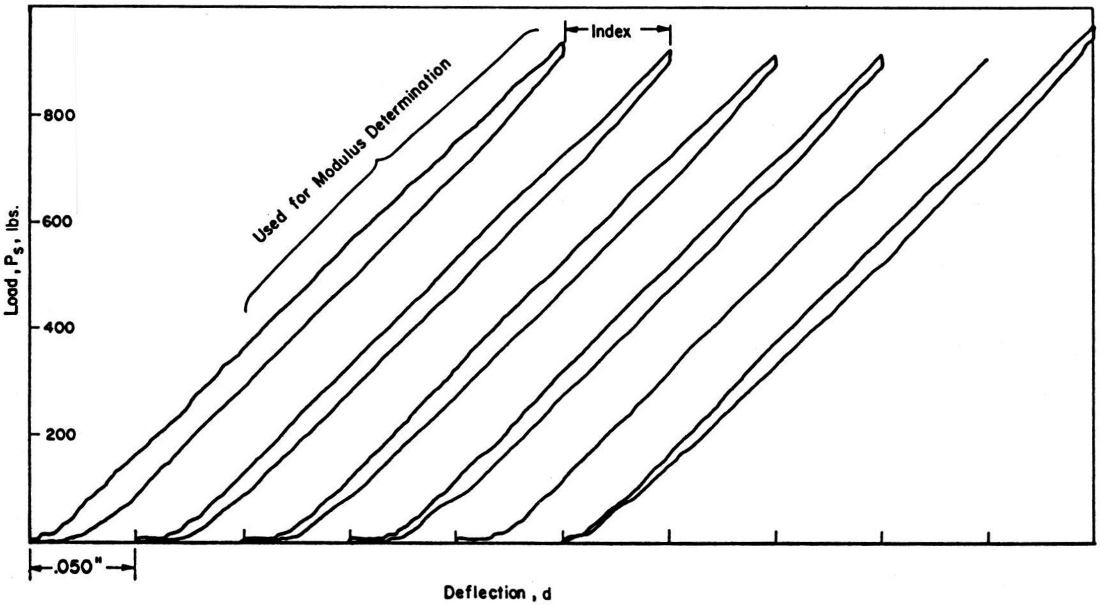


Figure A-8. Typical shear load-deflection record.

at zero load but is shown elsewhere on the figure for clarity.

The low-temperature tests were carried out at 40 F, 20 F, 0 F, —20 F, and —40 F (sample temperature). A series of cold-box trials was run to investigate the time necessary to ensure that the sample was at the desired

TABLE A-1

GROUP A EXPERIMENTAL DATA

Sample	Width a	Length b	Thickness t	Temperature T	Hardness D	--- Shear Modulus --- $G_{average}$	$G_{last\ run}$	G_{final}	Stress Relaxation	Modulus Increase with time
A-1S	3.02	6.06	.54	-40	51	153	162	211	12.0	38
A-1D	3.04	5.95	.50	-40	57	430	481	830	11.8	93
A-2S	3.01	6.05	.52	-20	50	125	136	214	9.9	71
A-2D	3.04	6.02	.50	-20	57	332	404	1173	8.7	254
A-3S	3.02	6.09	.51	0	52	104	109	162	8.1	56
A-3D	3.00	6.00	.50	0	57	273	314	764	8.0	180
A-4S	3.03	6.09	.51	20	51	105	108	121	4.8	15
A-4D	3.02	5.98	.50	20	57	156	181	316	6.9	103
A-5S	3.00	6.06	.53	40	51	101	104	110	5.2	9
A-5D	3.03	5.98	.50	40	57	140	156	206	6.3	47
A-6S	3.05	6.15	.50	75	51	100	102	93	3.3	7(b)
A-6D	3.00	6.00	.50	74	57	122	127	141	4.9	16(b)
A-6N (1)	3.15	6.20	.44	76	30	45	45	45	2.8	0(b)
A-6NR	3.03	6.00	.48	76	47	80	80	82	1.4	2(b)
A-6E	3.12	6.20	.49	76	53	85	87	88	5.4	4(b)
A-9S	2.98	5.93	.53	-40	61	236	261	576	14.7(a)	144
A-10S	3.00	5.95	.53	0	60	186	204	371	11.7	100
A-11S	3.10	5.96	.50	40	60	121	127	136	6.3	12
A-12S	3.06	6.05	.52	77	60	114	117	114	4.9	0(b)
A-12N(1)	3.12	6.10	.46	76	41	63	63	65	4.0	3(b)
A-12NR	3.00	6.05	.48	77	58	127	128	127	2.6	0(b)
A-12E	3.15	6.10	.54	76	61	116	120	126	5.9	9(b)
A-13S	3.05	6.05	.57	-40	70	369	411	741	17.0(a)	101
A-14S	2.97	5.95	.57	0	70	251	297	468	10.6	86
A-15S	3.01	6.07	.53	40	71	177	191	215	6.0	21
A-16S	3.08	6.10	.54	76	70	170	185	188	5.3	11(b)
A-16N(1)	3.05	6.12	.46	76	55	102	110	117	5.3	15(b)
A-16NR	3.00	6.00	.47	76	69	206	211	210	3.6	2(b)
A-16E	3.06	6.02	.56	76	72	184	193	199	6.1	8(b)
A-18S	6.00	12.00	.51	76	51	97	99	97	4.0	0(b)
A-18D	6.00	11.97	.50	76	57	121	126	125	4.6	3(b)
A-20S	3.02	12.04	.52	76	51	100	101	101	3.2	1(b)
A-20D	3.01	11.95	.50	76	57	120	122	117	4.2	3(b)
A-21D(2)	2.97	6.00	.50	77	57	123	128	136	5.2	11(b)
	inches	inches	inches	F	Shore A Durometer	psi	psi	psi	% per Decade	%

S = Neoprene
D = Neoprene-Dacron Combination
N = Natural Rubber
E = EPDM

(1) Replicate Samples
(2) Bonded to Steel Plates

(a) Initial Slope
(b) Room temperature increase represents considerably more than 6 hours.

temperature, and to investigate the relation between temperatures of the sample and the air in the cold box. It was found that the sample could be brought to a steady-state condition in 1 hr by initially reducing the cold-box temperature to somewhat less than the test temperature, and then raising the temperature back to that desired shortly before initiating the shear cycling. These low-temperature tests were run in much the same manner as those at room temperature, with the exception that the stress relaxation phase could not be allowed to run overnight because of the necessity of monitoring the quantity of liquid nitrogen remaining in the system. Figure A-9 shows the shear "set" visible in a sample immediately following a test at —40 F.

Throughout each test run, sample condition was observed and noted for elastomer deterioration, bond tearing, shear "set" (failure of the sample to return to the original zero deflection), and any other effect that could be of some importance.

RESULTS

Each sample run produced a recorder graph of shear load (P_s) versus shear deflection (d); a typical run is shown in Figure A-8. From these traces, a slope was estimated in the portion of the curve as shown, and a shear modulus was computed as follows:

$$G = \frac{(t)\ (\Delta P_s)}{2ab\ (\Delta d)}\ \text{psi} \qquad \text{(A-1)}$$

in which

$G =$ shear modulus, psi;
$t =$ sample thickness, average of two, inches;
$a =$ sample width, average of two, inches;
$b =$ sample length, average of two, inches;
$\Delta P_s =$ shear load over part of curve, pounds; and
$\Delta d =$ shear deflection over same part of curve, inches.

An average shear modulus (G_{avg}) was computed from the results of the first five loading cycles; a shear modulus was computed for the fifth cycle ($G_{\text{last run}}$) and for the sixth and final cycle after stress relaxation (G_{final}). The results of these calculations are given in Table A-1, together with the geometry and hardness data for each sample.

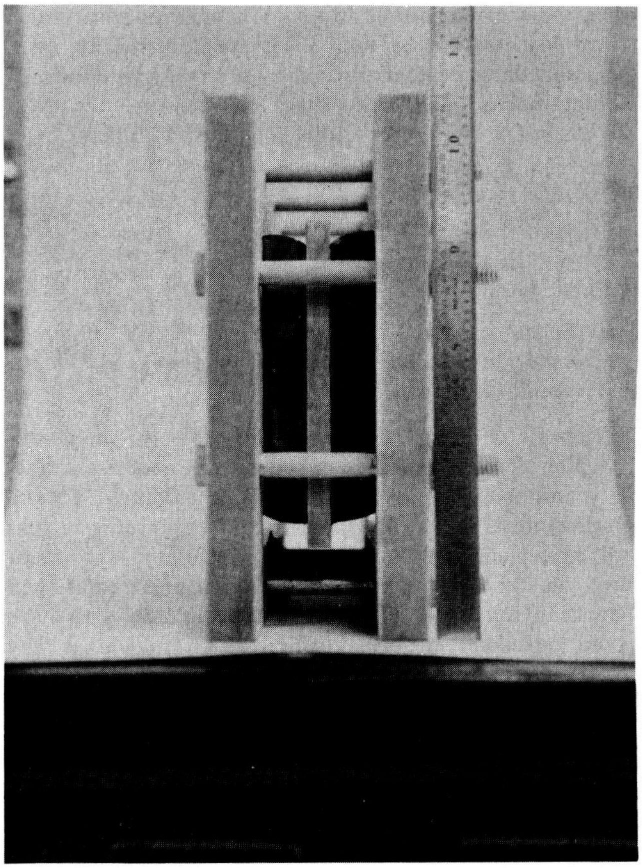


Figure A-9. Shear "set" following low-temperature test.

Figure A-10 shows a typical shear load-time history;

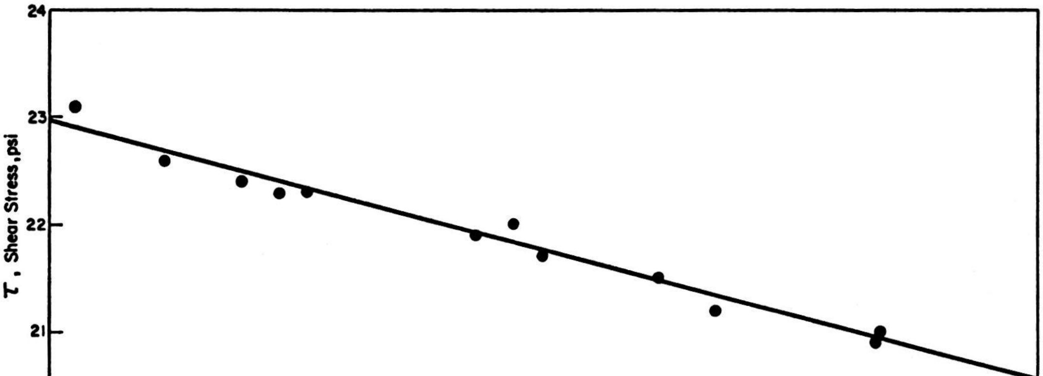


Figure A-10. Typical shear stress-time graph; constant 50 percent shear strain.

when the shear load-time history is plotted as shear stress (shear load divided by total shear area) versus log time, the result may be approximated by a straight line through the data points. The slope of this line represents the stress relaxation for the sample and is computed as follows:

$$\text{Stress relaxation} = \frac{(\tau_1 - \tau_n)\ (100)}{(\tau_1)\ (n)}$$

$$= \text{percent per decade of time} \qquad \text{(A-2)}$$

in which

τ_1 = shear stress at 1 min, psi;
τ_n = shear stress after n decades of time, psi; and
n = number of decades of time.

The results of these calculations are given in Table A-1.

A plot of sample hardness taken with a Shore A durometer versus the computed average shear modulus at room temperature is shown in Figure A-11. This plot is in general agreement with information available in the literature; the trend is for an increase in shear modulus with increasing hardness. Note, however, that the data have by no means an exactly definable relationship; rather they are represented by a band. The hardness of a sample is therefore only a relative indication of shear modulus.

Figure A-12 shows the expected trend of higher shear modulus with decreasing temperature Every attempt was made during the investigations to assure that the same elastomer properties were being represented at low temperature as at room temperature, so that the nominal hardnesses indicated on the graph should have only relative importance. For the 50-durometer samples, shear modulus increase was small until the temperature reached about —20 F, whereas both the 60- and 70-durometer samples exhibited considerable shear modulus increase at less than 40 F. Also to be noted is the comparison between the two apparently different formulations of 60-durometer neoprene; the neoprene-dacron combination experienced a far greater shear modulus increase at low temperatures than did the neoprene samples.

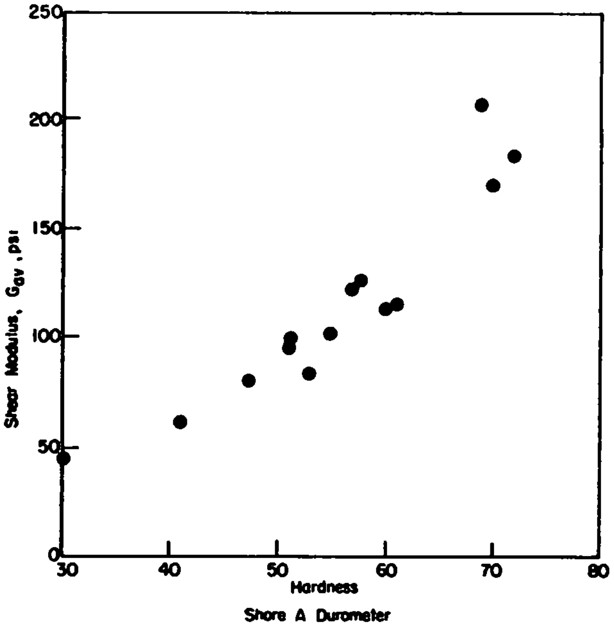


Figure A-11. Shore A durometer hardness versus shear modulus (G_{avg}).

Figure A-13 shows a graph of stress relaxation versus shear modulus; the higher shear moduli were those obtained at low temperatures. Although the data points cover a wide band, it is interesting that the general trend is for greater stress relaxation at lower temperatures (higher moduli). It must be pointed out, however, that the stress relaxation at low temperatures covered a period of only about 5 hr and that some decrease in the rate of stress relaxation was apparent at that time in at least two samples.

The increase in shear modulus with length of time under strain is shown as a percent versus the sample test temperature in Figure A-14. This increase was calculated as follows:

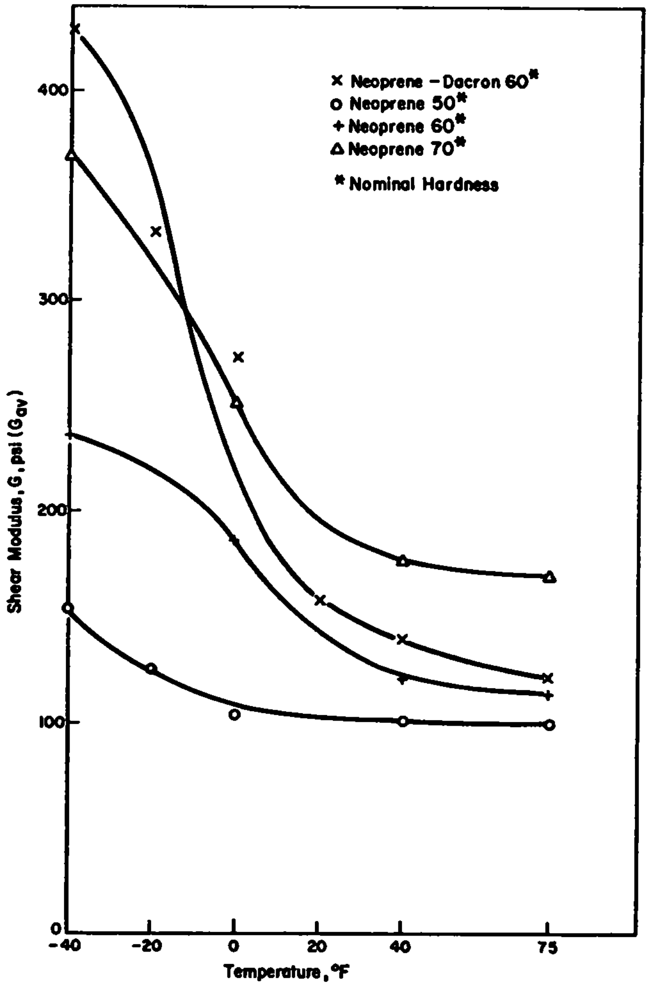


Figure A-12. Shear modulus (G_{avg}) *versus temperature.*

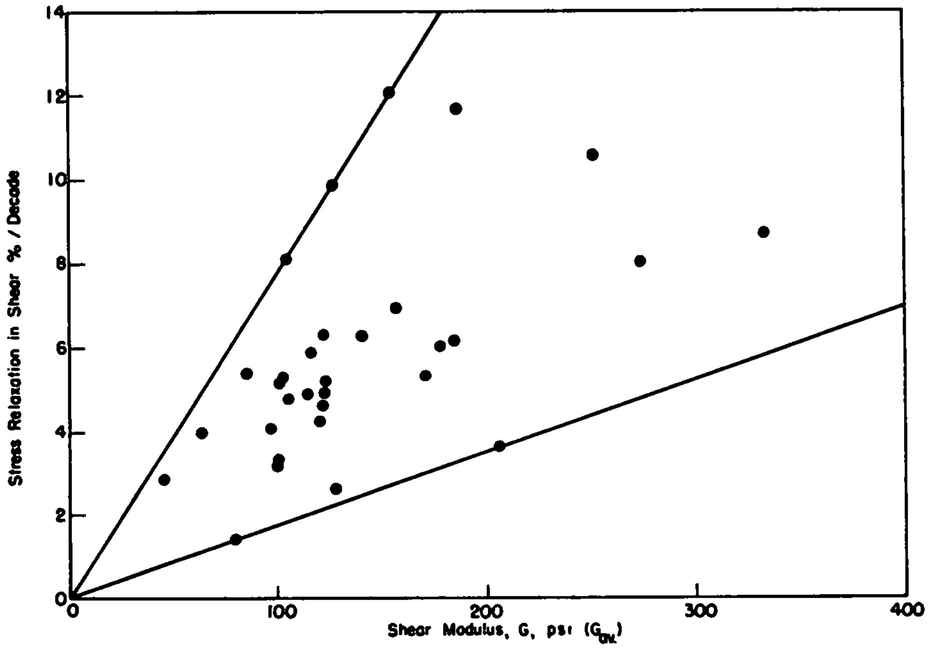


Figure A-13. Stress relaxation versus shear modulus (G_{avg}) at 50 percent shear strain.

$$\text{Percentage increase in shear modulus} = \left(\frac{G_{final}}{G_{avg}} - 1\right) \times 100 \qquad \text{(A-3)}$$

The shape of these curves reveals that for neoprene there is a temperature (about −20 F) at which this modulus increase occurs most rapidly. The fact that the curves drop off below this temperature points to the crystallization phenomenon as the cause of the increase. The effect of crystallization was more apparent in the nominally 60-durometer neoprene-dacron combination than in any of the other neoprene samples, probably due to the difference in formulations.

One final observation is that in none of the samples was either bond or elastomer tearing a problem. In fact, although one of the neoprene-dacron samples had about a ½-in. void at the start of one test, this void did not enlarge at all during the series of shear cycles. At low temperatures there was a tendency for the neoprene-dacron samples to slip between the steel plates at high shear loads, but this posed no significant obstacle to obtaining modulus data.

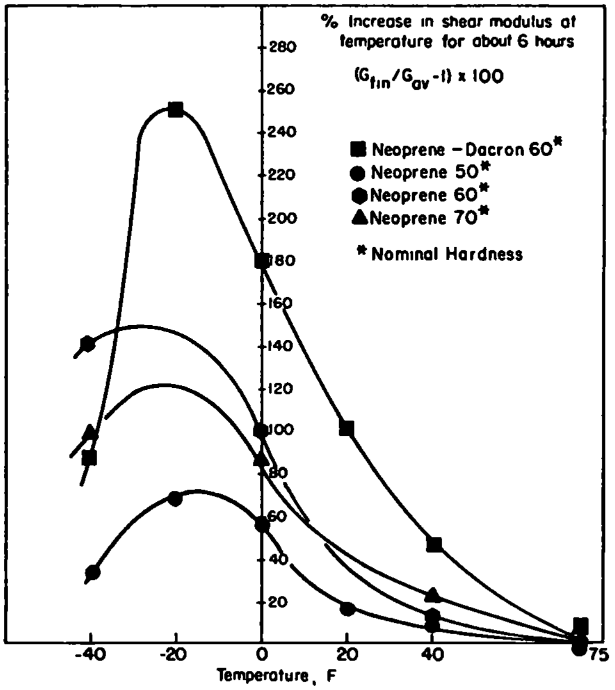


Figure A-14. Increase in shear modulus with time at constant temperature.

APPENDIX B

GROUP B—COMPRESSION BEHAVIOR

The Group B experiments covered the effects of geometry, lamination, and holes on the compressive stress-strain behavior of bearing samples ranging in size from laboratory specimens (down to 9 sq in.) to full size (up to 266 sq in.). Materials were neoprene, natural rubber, and EPDM bonded to steel plates, and neoprene-dacron combination. Shape factor ranged from about 1 to 15; number of laminates, from 1 to 18; and hardness, between 50- and 70-durometer. All tests were run at room temperature. In all cases, compressive stress-strain behavior was compared to that predicted by both theoretical and empirical approaches.

EQUIPMENT

Two machines were used in the Group B experiments because of the large range of compressed sample areas. The smaller machine was a Baldwin-Southwark hydraulic compression-tension test unit, used here in its compression mode. The maximum machine capacity is 60,000 lb, with six load ranges to facilitate accurate results on small samples. As in the Group A test series, coupled to the unit is (1) a direct readout of platen movement through a tape drive, and (2) a load/deflection recorder (pen on graph). This latter device records (1) the load through a mechanical-pneumatic hook-up, and (2) the relative deflection of the moving platen to the fixed crosshead by a motor driven from the output of an LVDT (extensometer). As used in the Group B experiments, the recorder provides a permanent graph of compressive load versus compressive deflection. The larger machine was a Tinius-Olsen hydraulic compression-tension test unit with a maximum capacity of 400,000 lb and six load ranges. Its operation was in most respects similar to the smaller Baldwin unit, with the added convenience of an electronic deflection-rate indicator, which made it possible to maintain a constant strain rate by holding the pointer at a predetermined location on the indicator. In all cases, a piece of flat ½-in. steel plate was inserted between the sample and the upper crosshead to assure even loading, as when the sample extended somewhat beyond the width of the crosshead. The upper crosshead was 20 in. wide, whereas the largest samples were nominally 22 in. wide; the loaded overhang was 1 in. on each end and in the lowest stressed area of the bearing surface. This plate was found necessary when the center section of sample B-26S was extended somewhat through the center tension grip hole in the upper crosshead. Figure B-1 shows the Tinius-Olsen unit with a large sample placed between the platen and crosshead.

METHOD

Compression test samples were cut from the appropriate sheet stock with a single shear stroke from a pneumatically operated blade. The materials were neoprene, natural rubber, EPDM, and neoprene bonded to dacron; sheet stock was nominally ¼, ½, and 1 in. thick in 50-, 60-, and 70-durometer (Shore A durometer). The areas ranged from 9 to 266 sq in. Plates shear-cut from ¼-in. steel were bonded on each side of single-laminate bearings and also between the elastomer sheets on multiple-laminate bearings. The bonding method is described in Appendix E. Exceptions to this were the neoprene-dacron samples, these were placed, rather than bonded, between the steel plates. Laminated neoprene-dacron bearings did not have steel plates between elastomer sheets. To assure an adequate edge bond, all steel plates were cut ½ in. larger than the sample dimensions of length (*b*) and width (*a*) Length, width, and thickness were recorded for each sample and are given in Table B-1. The final eight samples had holes cut in them to the diameter shown, but the bonding procedure remained the same.

Each finished sample was placed in the center of the machine platen and loaded at an arbitrary 4 percent compressive strain per minute to a total of 20 percent strain (based on original thickness) or 2,000 psi, whichever occurred first. In several cases involving the larger bearings, the load limits of the test machine precluded reaching the 2,000 psi. The sample was then unloaded to the starting point and the load-unload cycle was repeated a total of four times to assure conditioning. Figure B-2 shows a large bearing prior to loading, and loaded to 2,000 psi, respectively. All load-deflection data were recorded on graph paper and the bearing samples were observed for bond tearing and elastomer deterioration. As a result of a general lack of good bond adhesion observed during the testing, four replicate bearings were prepared with particular attention to proper bonding. These were then tested, and are denoted by an "R" after the sample designation in Table B-1. All tests were run in a temperature- and humidity-controlled laboratory at 75 F ±1.

RESULTS

All data were recorded in the form of compressive load (P_c) versus compressive deflection (δ_c) curves, as shown by Figure B-3. The deflection scale was indexed after each load-unload cycle to avoid overlapping curves. The index was established at zero load but is shown elsewhere on the

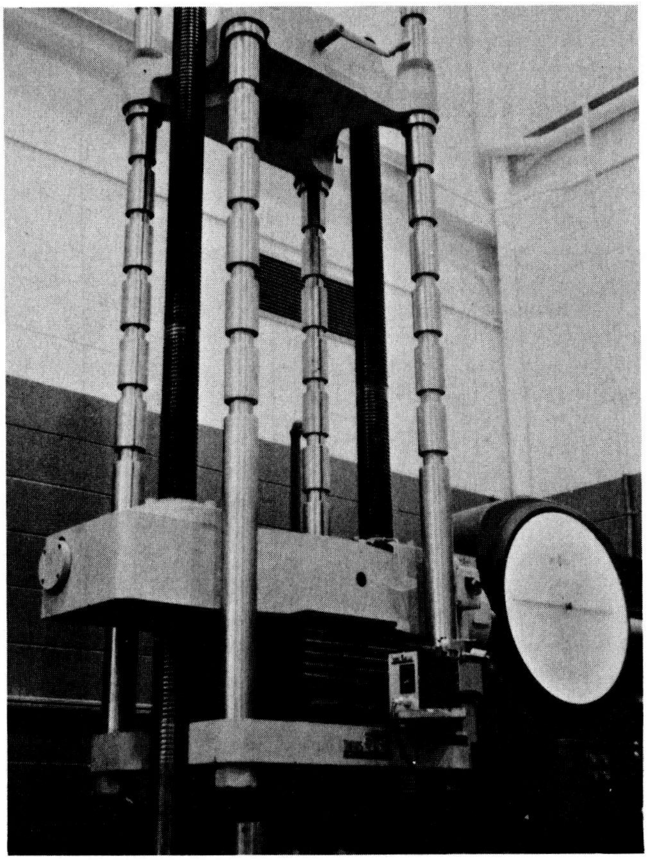


Figure B-1. Tinius-Olsen compression test machine.

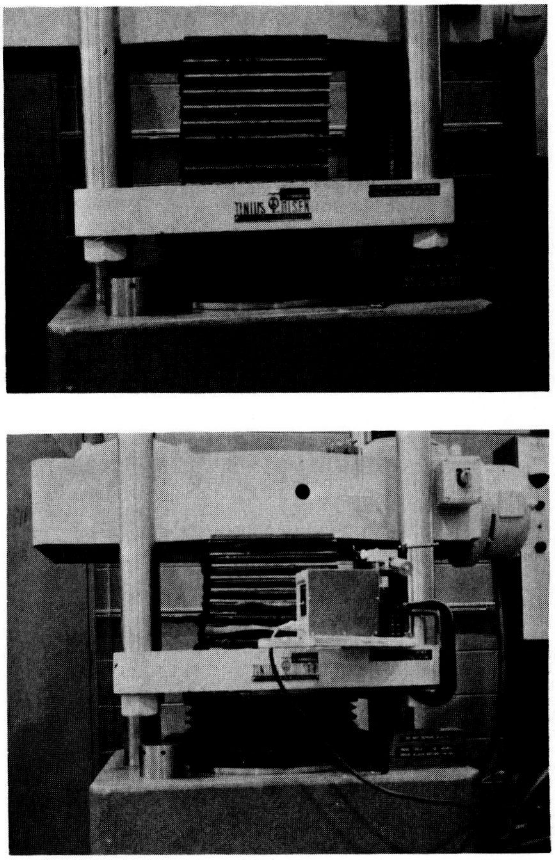


Figure B-2. Sample B-185 prior to loading (upper) and during loading (lower).

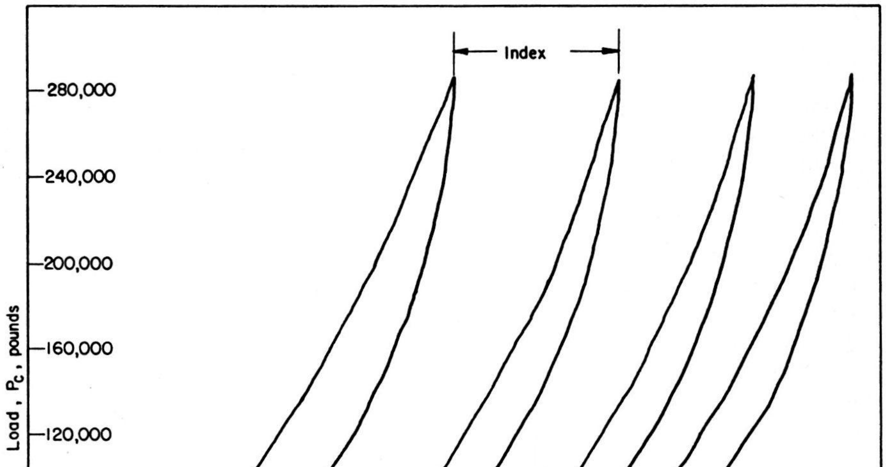


Figure B-3. Typical compression load-deflection record.

figure for clarity. The compressive behavior of each bearing was predicted in each case, from the value of shear modulus obtained in the Group A experiments, with the use of the modified theoretical approach using the digital computer and also the empirical approach (see Appendix F). For each bearing, then, the theoretical and empirical predictions were placed on a plot of load (stress) versus deflection (strain), using the same scales as the original sample data. Because of some question about the zero point or origin on each experimental curve, it was decided to "fit" the curve to a reference point of 100 psi and shift it to agree there with the theoretical prediction. This was done in each case; representative graphs are shown in Figures B-4 through B-17. Plots for all tests are available by contacting the Progam Director, NCHRP. The computed value of shape factor is shown for each bearing. The heavy solid line represents the experimental results (labeled EXP); the dashed line, the theoretical approach (labeled THE); and the light solid line, the empirical approach (labeled EMP). (See Appendix F)

TABLE B-1

GROUP B EXPERIMENTAL DATA

Sample	Width a	Length b	Thickness t	Shape Factor S	Nominal Hardness D	Number of Laminations n	Hole Diameter
B-1S	3.02	3.02	0.53	1.42	51	1	
B-1D	2.98	3.00	0.50	1.49	57	1	
B-2S	3.01	3.03	0.53	1.42	70	1	
B-3S	2.98	6.04	0.51	1.96	51	1	
B-3D	2.97	6.01	0.50	1.99	57	1	
B-3N	3.01	6.02	0.47	2.13	47	1	
B-3E	2.99	5.60	0.52	1.87	53	1	
B-4S	3.01	6.07	0.51	1.97	60	1	
B-4N	3.07	6.01	0.47	2.16	58	1	
B-4E	3.03	5.91	0.54	1.85	61	1	
B-5S	3.02	6.01	0.53	1.90	70	1	
B-5N	3.00	6.04	0.46	2.18	69	1	
B-5E	3.00	5.99	0.56	1.78	72	1	
B-6S	3.02	12.05	0.50	2.41	51	1	
B-6D	3.05	12.00	0.50	2.43	57	1	
B-7S	2.95	11.88	0.51	2.32	70	1	
B-8S	5.98	5.99	0.51	2.93	51	1	
B-8D	5.97	6.02	0.50	3.00	57	1	
B-9S	5.98	6.04	0.50	3.00	51	4	
B-9D	6.02	6.02	0.50	3.01	57	4	
B-10S	6.00	6.04	0.49	3.07	51	7	
B-10D	5.96	5.98	0.50	2.98	57	7	
B-11S	6.06	6.09	0.54	2.81	70	1	
B-12S	5.99	12.01	0.50	4.00	51	1	
B-12SR(1)	6.00	12.04	0.53	3.77	51	1	
B-12D	6.04	12.00	0.50	4.02	57	1	
B-12N	5.98	12.00	0.50	3.99	47	1	
B-12E	6.00	11.95	0.55	3.63	53	1	
B-13S	5.99	11.98	0.49	4.07	51	4	
B-13D	6.03	12.04	0.50	4.02	57	4	
B-14S	6.00	12.03	0.50	4.00	51	7	
B-14D	6.03	12.02	0.50	4.02	57	7	
B-15S	5.98	12.00	0.50	3.99	51	18	
B-16S	6.02	11.99	0.49	4.09	60	1	
B-17S	12.05	22.09	1.00	3.90	51	1	
B-18S	11.99	22.00	0.98	3.96	51	9	
B-19S	6.02	22.09	0.50	4.73	51	1	
B-19D	6.02	21.92	0.50	4.72	57	1	
B-20S	6.02	22.04	0.48	4.93	51	4	
B-20D	6.04	22.01	0.50	4.74	57	4	
B-21S	6.01	22.03	0.51	4.63	51	7	
B-21D	6.04	22.13	0.50	4.74	57	7	
B-22S	6.03	22.10	0.53	4.47	70	1	
B-23S	11.97	12.02	0.52	5.77	51	1	
B-23SR(1)	11.97	12.02	0.51	5.91	51	1	
B-23D	11.95	11.99	0.50	5.98	57	1	
B-24S	11.96	12.00	0.50	5.99	51	4	
B-24D	12.03	12.07	0.50	6.02	57	4	
B-25S	11.99	12.01	0.51	5.88	51	7	
B-25D	12.06	12.10	0.50	6.04	57	7	
B-26S	11.98	12.00	0.53	5.66	70	1	
B-27S	6.06	11.98	0.26	7.74	51	1	
B-27N	6.08	12.04	0.22	9.18	47	1	
B-27E	5.96	11.94	0.27	7.36	53	1	
B-28S	5.99	11.97	0.27	7.39	51	4	
B-29S	6.00	11.95	0.27	7.40	51	7	
B-30S	6.04	12.00	0.27	7.44	60	1	
B-31S	6.03	24.05	0.27	8.93	51	1	
B-32S	6.01	23.75	0.28	8.56	70	1	
B-33S	9.01	9.05	0.25	9.03	51	1	
B-33SR(1)	9.04	9.04	0.25	9.21	51	1	
B-34S	9.00	9.12	0.26	8.71	70	1	
B-35S	9.04	18.10	0.26	11.6	51	1	
B-35SR(1)	8.99	18.08	0.25	12.0	51	1	
B-35N	9.00	16.80	0.24	12.2	47	1	
B-35E	9.04	17.50	0.28	10.6	53	1	
B-36S	9.01	18.06	0.27	11.1	60	1	
B-37S	9.06	17.96	0.27	11.2	70	1	
B-38S	9.03	27.08	0.24	14.1	51	1	
B-39S	9.00	27.10	0.28	12.1	70	1	
B-40S	3.00	6.04	0.50	1.78	51	1	5/8"
B-40S	3.01	6.04	0.50	1.59	51	1	1-1/8"
B-40S	3.01	6.06	0.50	1.44	51	1	1-1/2"
B-40S	3.01	6.06	0.50	1.29	51	1	2-1-1/8"
B-40D	2.98	6.01	0.50	1.81	57	1	1/2"
B-40D	2.99	5.99	0.50	1.62	57	1	1"
B-40D	3.00	6.01	0.50	1.43	57	1	1-1/2"
B-40D	3.00	5.92	0.50	1.34	57	1	2-1"
	inches	inches	inches		Shore A Durometer		

(1) Replicate samples

S = Neoprene
D = Neoprene-Dacron Combination
N = Natural Rubber
E = EPDM

During the actual experimental work, it was observed that almost all bearings "squeezed out" to some extent because of inadequate bonding. This ranged from an inch of missing bond to several cases where more than half the bond was inadequate. The combination of nonflat steel plates and nonflat elastomer sheets contributed to this problem. The recommended 7-mil thickness of bonding agent was not enough to make up for the waviness of the mated surfaces. No quantitative estimate of remaining bond could be made during the testing, however, so it was decided to make a judgment from the shape of the curves to allow the rejection of certain sample data. Another factor leading to this decision was the comparison of the replicate bearing data The bonding for all replicate bearings was carefully done, and all these bonds exhibited excellent holding However, the comparison did not show that the other bearings were always softer, as might be expected when some areas of a bearing are unbonded. The experimental error, including variations in material properties, was judged to be of the same order of magnitude as the effects of a variation in bonding. With this in mind, the data from eight of the samples were judged unacceptable for reasons of bonding (as evidenced by the shape of the stress-strain curve). The fact that three of the six EPDM samples produced unacceptable data is due to that material's poor affinity to the bonding agent used, and not necesarily to poor material.

From the remaining sample curves the values of compressive strain at 500, 1,000, 1,500, and 2,000 psi compressive stress were recorded and compared with the values predicted both by the theoretical and the empirical approaches. Initial judgment was that for low values of shape factor (1 to 4), the theoretical predictions of compressive behavior were adequate; for medium shape factors (3 to 5), the empirical approach appeared valid. However, for higher values of shape factor, neither available prediction gave accurate results. Therefore, a total analysis of the data was attempted to correlate compressive stress-strain behavior empirically for the range of shape factors investigated. Because the data scatter was substantial, a straight-line approximation was made on a log-log plot of shape factor versus compressive strain, at

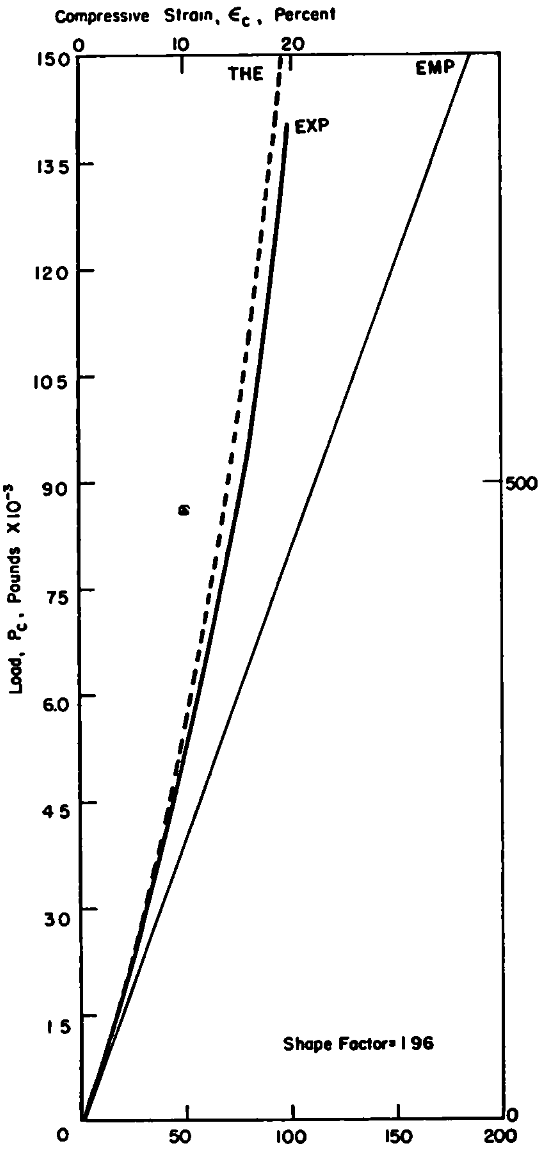


Figure B-4. Compression of sample B-35.

a constant hardness and compressive stress. Figure B-18 shows the result of one such curve for 50-durometer and 500 psi. Evident in this figure is the spread of experimental data. This curve-fit was accomplished by using a least squares regression "best fit" of the data to an expression of the form

$$\epsilon_c = a\,S^b \text{ (constant hardness, compressive stress)} \qquad \text{(B-1)}$$

in which

ϵ_c = compressive strain, percent; and
S = shape factor = one loaded area — total free area.

Once the curves were plotted and analyzed, it became apparent that the nominally 60-durometer neoprene-dacron behaved somewhat "softer" than expected and the curves for this material were derived separately. Too few data points then remained at 60-durometer, so only 50- and 70-durometer curves were fit. The resulting constants for Eq. B-1 are given in Table B-3.

For uniformity of presentation and to put the results of the data analysis in a reasonable form for use in design efforts, the log-log curve information was plotted as compressive stress-strain curves for constant shape factor (Figs.

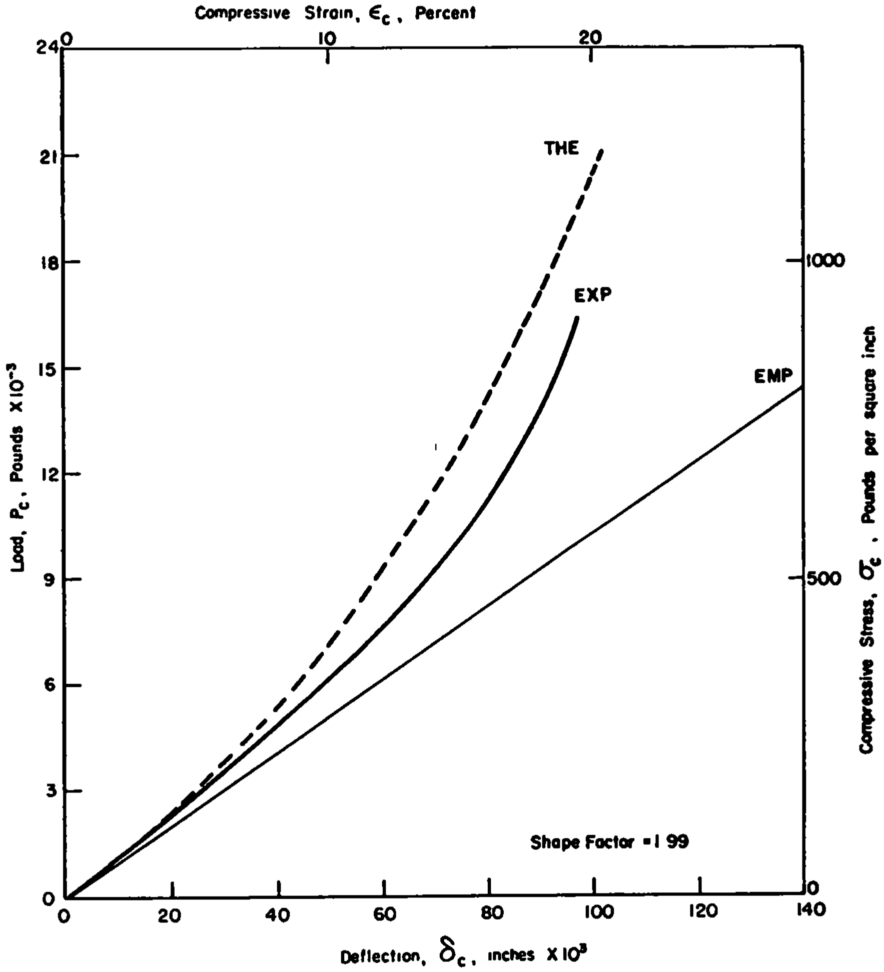


Figure B-5. Compression of sample B-3D.

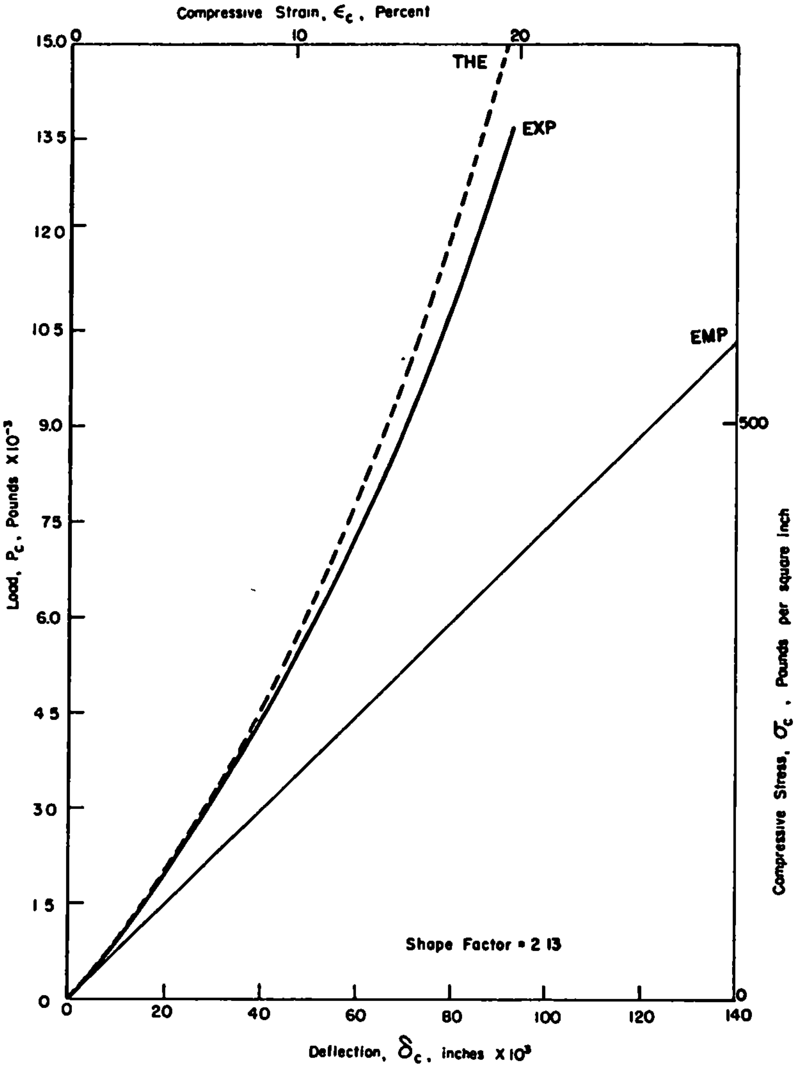


Figure B-6. Compression of sample B-3N.

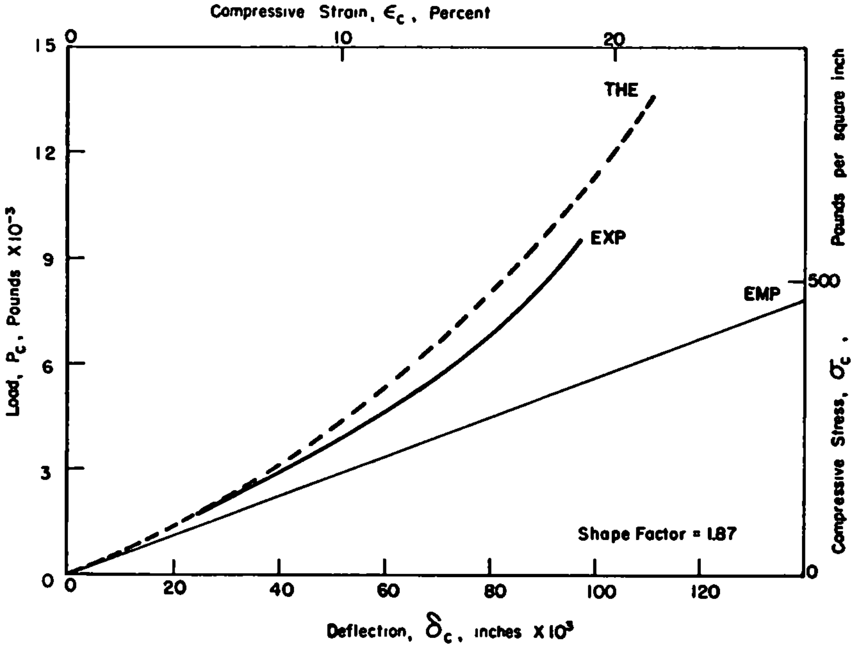
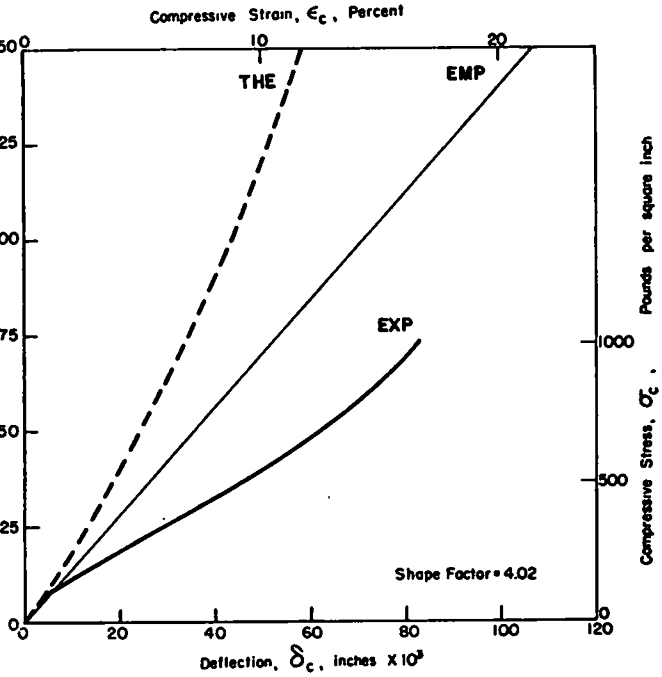


Figure B-7. Compression of sample B-3E.



ure B-8. Compression of sample B-12D

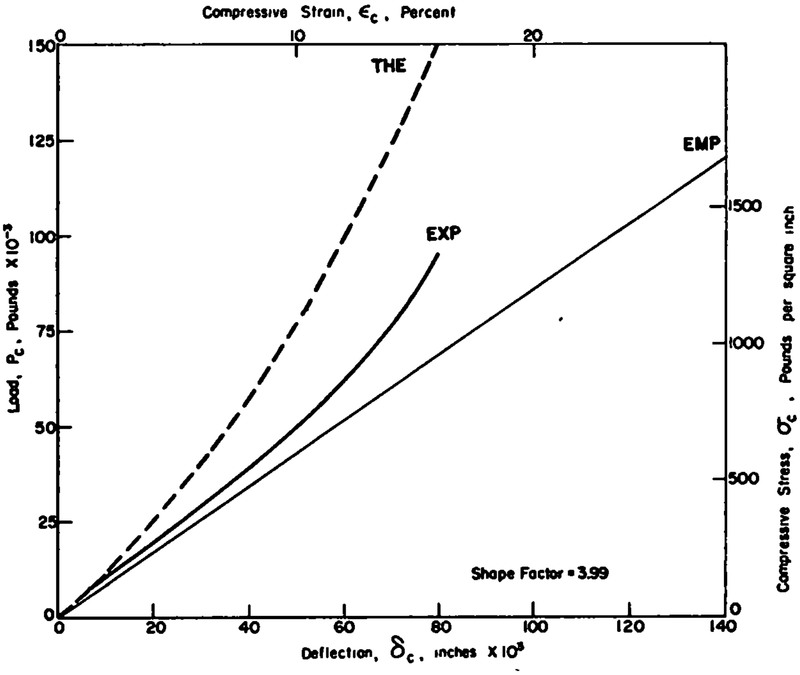


Figure B-9. Compression of sample B-12N.

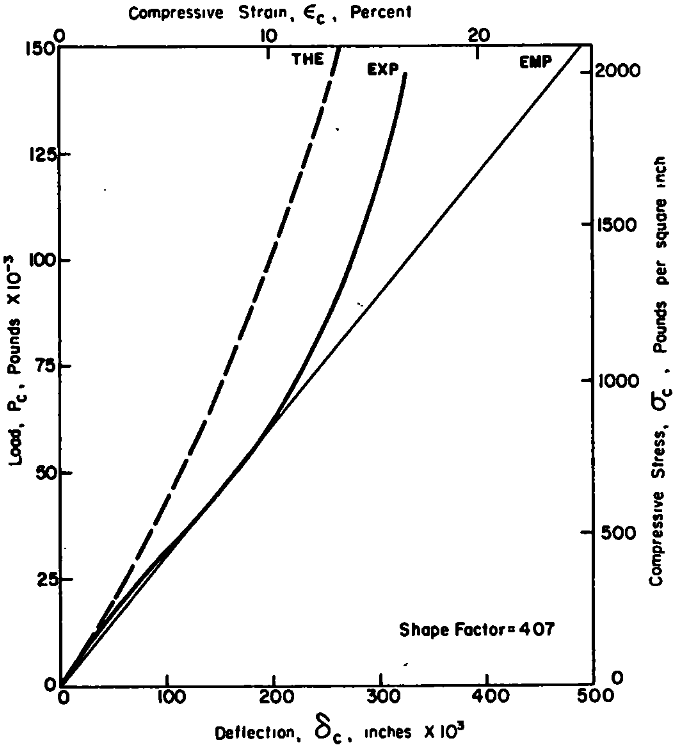


Figure B-10. Compression of sample B-13S.

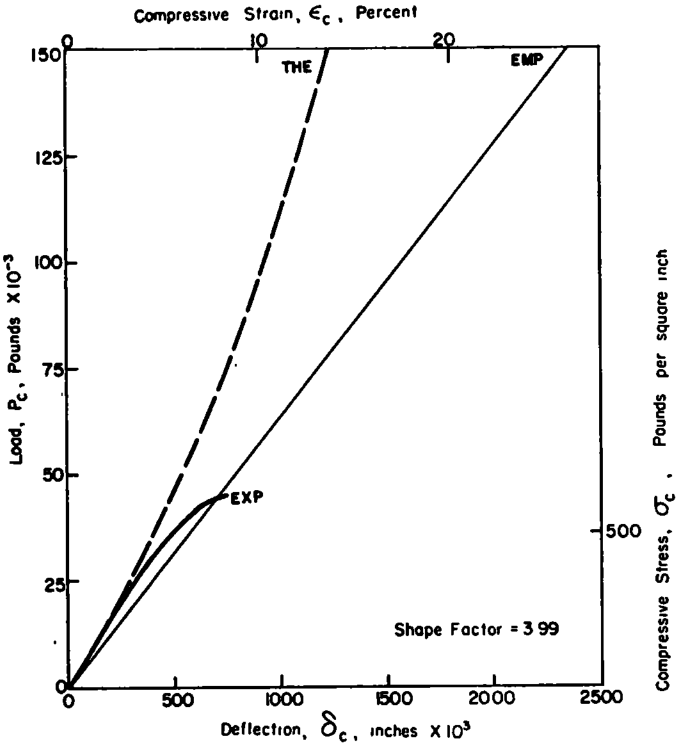


Figure B-11. Compression of sample B-15S.

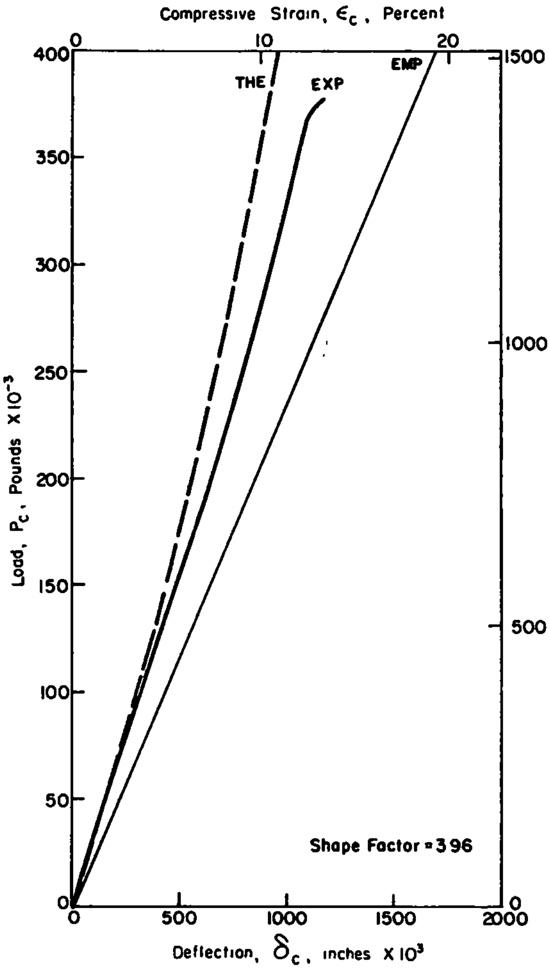


Figure B-12. Compression of sample B-18S.

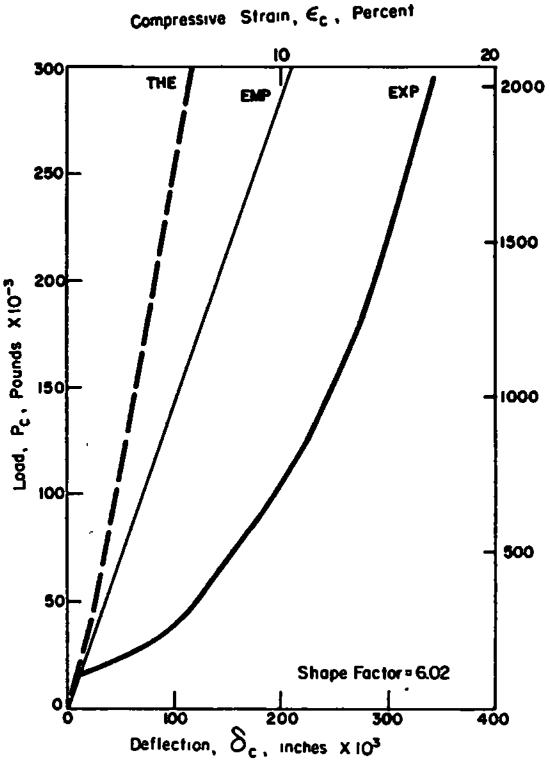


Figure B-13. Compression of sample B-24D.

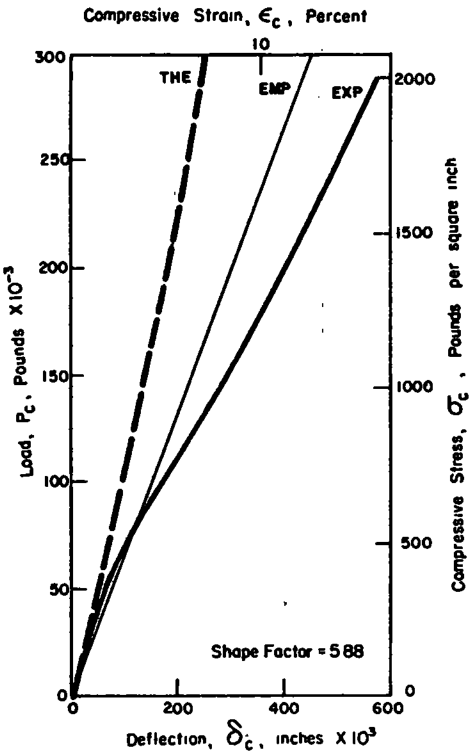


Figure B-14. Compression of sample B-25S.

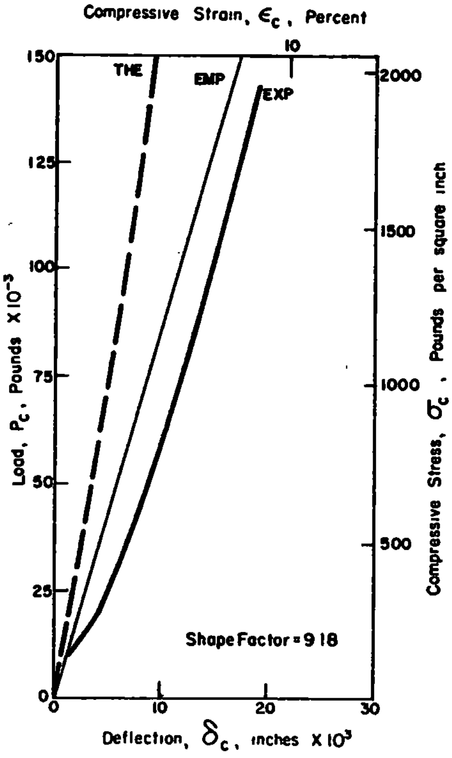


Figure B-15. Compression of sample B-27N.

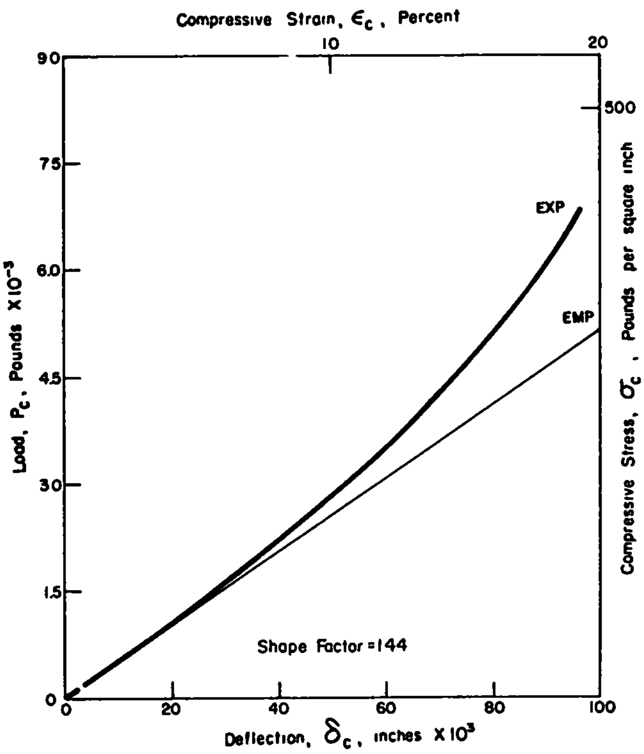


Figure B-16. Compression of sample B-40S (1½-in. hole).

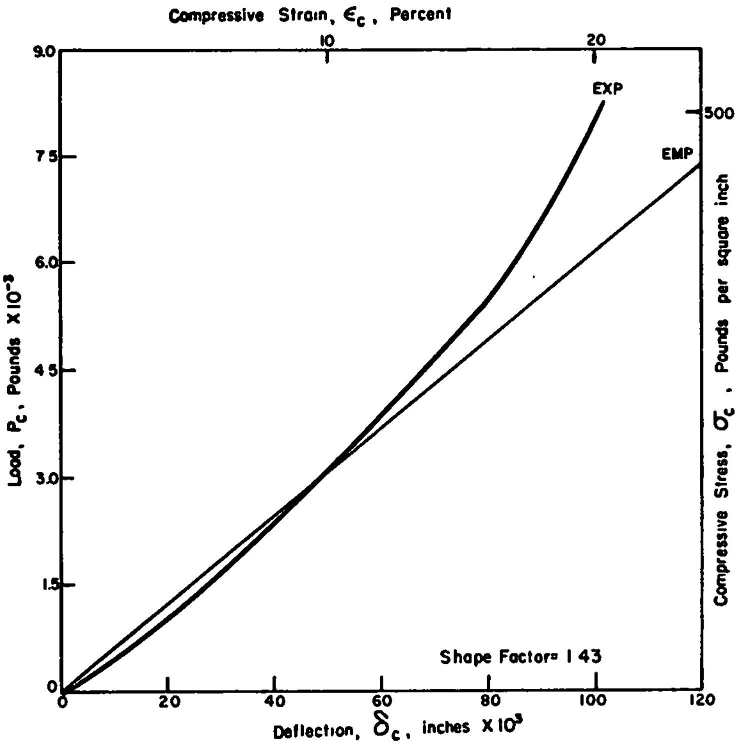


Figure B-17 Compression of sample B40D (1½-in hole)

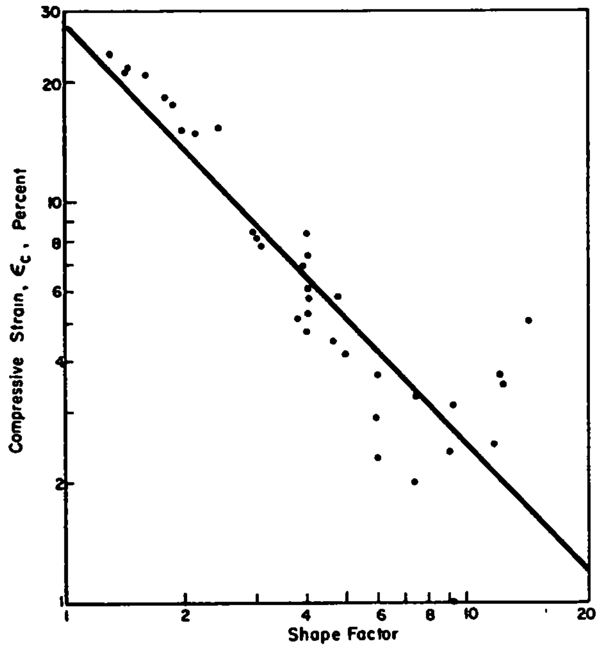


Figure B-18. Typical log-log plot of compression strain versus shape factor.

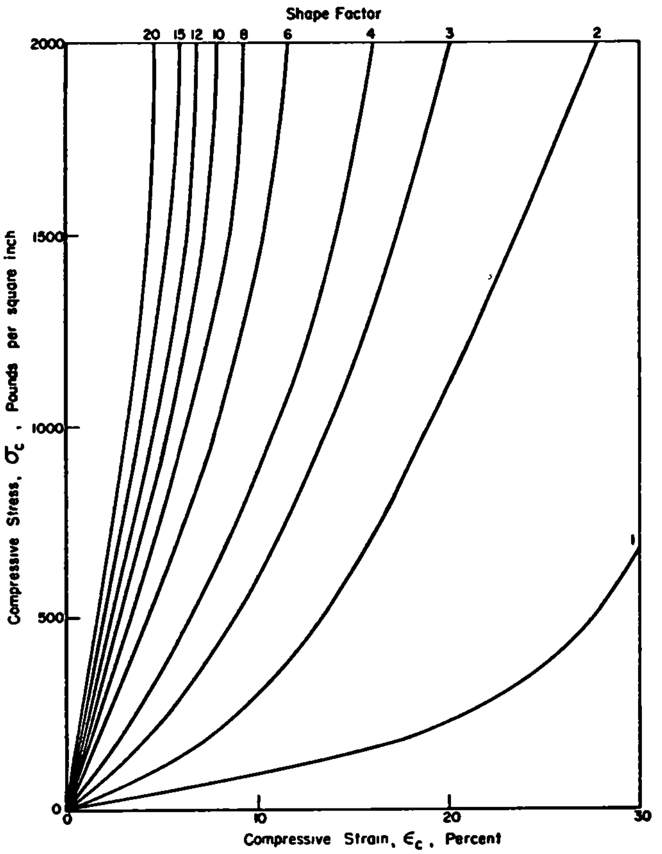


Figure B-19 Stress-strain in compression—50-durometer.

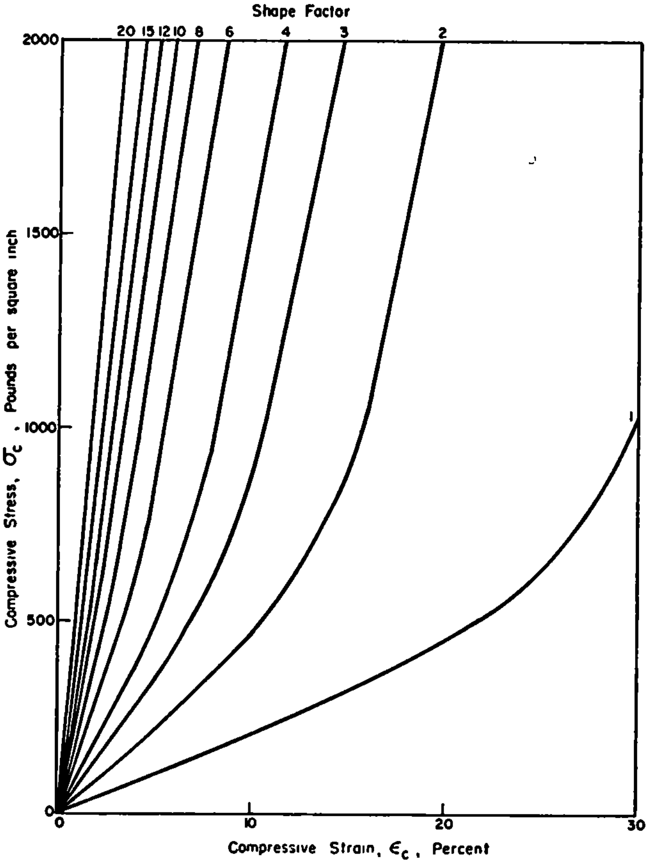


Figure B-20. Stress-strain in compression—70-durometer.

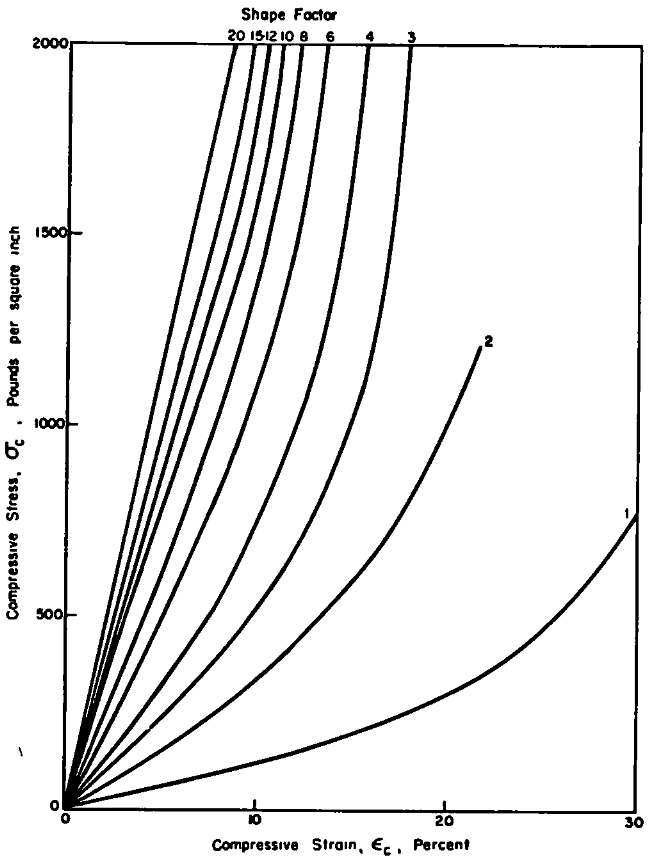


Figure B-21. Stress-strain in compression—57-durometer (neoprene-dacron).

B-19, B-20, and B-21). Whereas, again, these shape factor curves had to be "fit" to the empirically derived points at 500, 1,000, 1,500, and 2,000 psi, the fit was accomplished without much trouble and represents a further refining of the data to useable form.

The effects of lamination on compressive stress-strain behavior were investigated in this experimental group by bonding as many as 18 neoprene sheets together with steel plates between. Also investigated were neoprene-dacron bearings without bonding or steel plates. Descriptions of

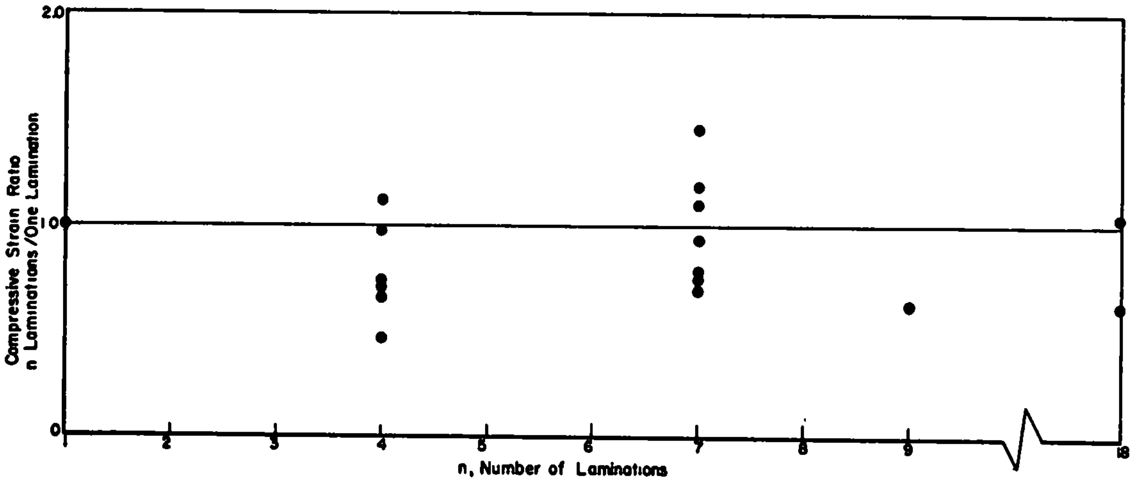


Figure B-22. Neoprene: effects of lamination on compressive strain.

the laminated bearings are given in Table B-1. For a given nominal shape factor, bearings were tested that differed only in number of laminations. With the compressive strain behavior of the single-laminate bearing assumed as the unit value, the strain of the multilaminate bearings was compared at 500, 1,000, 1,500, and 2,000 psi stress and these four values were averaged to determine a compressive strain ratio. This ratio was then plotted as shown in Figures B-22 and B-23 for neoprene and neoprene-dacron, respectively. For the 50-durometer neoprene, it appears from the graphs that there is no obvious effect of lamination on compressive bearing behavior. Any small effects are of necessity obscured by the range of experimental data, the sampling is too small to interpret the results statistically. On the other hand, it seems likely that for neoprene-dacron of constant shape factor, the greater the number of laminations, the greater the compressive strain. The number of data points is too few, however, to make any quantitative evaluation of this effect.

The effect of holes is evident in the compressive behavior of the eight bearings, B-40 (Table B-1) Although there is no theoretical prediction for these bearings, the empirical approach may be used with the calculated shape factor to predict the behavior. In short, the holes of the sizes used changed the shape factor significantly, and the behavior was altered in the direction and by the amount predicted. Figure B-18 of compressive strain versus shape factor shows that these data points do indeed lie near the best-fit curve. It is expected that this would be true for the effects of holes on larger shape factor bearings.

Although they were not one of the principal areas of investigation, it is important to point out that two bearings in the Group B experiments became unstable under compressive stresses of less than 2,000 psi. These were B-15S (Fig. B-11) and B-18S (Fig. B-12), both with a nominal shape factor of 4. The first had 18 laminations and became critical at about 600 psi; the second had 9 laminations and became critical at about 1,400 psi.

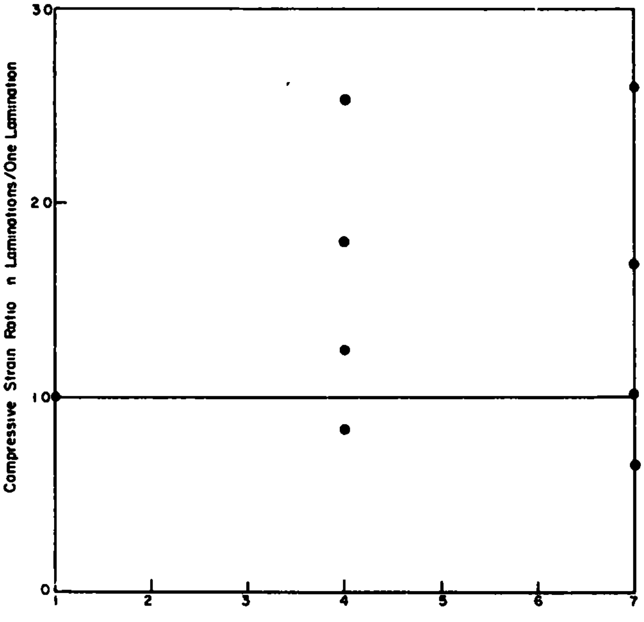


Figure B-23. Neoprene-dacron effects of lamination on compressive strain.

APPENDIX C

GROUP E—COMMERCIAL BEARINGS, SHEAR AND COMPRESSION

The Group E experiments covered the behavior in shear and compression of commercial bridge bearings of two types: neoprene vulcanized and bonded to steel plates, and neoprene vulcanized and bonded to dacron sheets. The test conditions were designed to simulate actual bridge bearing emplacements as nearly as possible, but without rotation or temperature changes. Tests were run in shear under constant compression between concrete surfaces to shear strains of ±50 percent, and in compression only to 2,000 psi stress. The hardness of all bearings was between 50- and 60-durometer. An attempt was made to determine the variation in elastomer material properties throughout the bulk of each bearing. Compressive stress-strain behavior was in all cases compared to that predicted by both theoretical and empirical approaches.

EQUIPMENT

The test set-up for use in the Group E experiments was designed around the same Tinius-Olsen 400-kip tension-compression machine used for part of the Group B experiments. With the intent of simulating actual bridge loading conditions on commercial bearings, three slabs were constructed of high-strength concrete with tie-rods cast in place. Short sections of I-beam were cut to fit between the ends of the tie-rods; steel plates were slipped over the tie-rod ends to take up the bearing shear loads. A pair of hydraulic cylinders with a hydraulic jack were obtained and calibrated to determine the cylinder pressure-load characteristics. These cylinders were then bolted between the I-beams and the central concrete slab. A magnetic mount attached to one of the hydraulic cylinders held a pointer which indicated the relative movement of the central slab to the upper and lower slabs; a scale fastened to an upper tie-rod allowed reading shear deflection to the nearest hundredth of an inch. A 3½-in. dial gauge mounted on the front of the hydraulic jack indicated cylinder pressure to the nearest 12 psi. The whole assembly was placed between the platens of the Tinius-Olsen machine to allow the maintenance of a constant compressive load during the shear loading. A schematic diagram of the test set-up is shown in Figure C-1. Compressive load was indicated on the face of a large dial gauge and the compressive load-deflection behavior was recorded continuously on the pen-recorder arrangement beside the loading dial. An added advantage during these experiments was the use of a solid-state feedback device coupled to the load readout on the Tinius-Olsen machine. One had only to come up to load and then engage this device, and the load was held constant within 0.5 percent. Figure C-2 shows the compression machine with the shear rig installed.

METHOD

Four pairs of full-sized 52-durometer neoprene commercial bearings laminated with steel plates (laminated and vulcanized simultaneously), and five pairs of 57-durometer neoprene commercial bearings laminated with dacron sheets were obtained for testing It was hoped that each laminate in a bearing would have the same thickness, and thus shape factor, however, this was definitely not the case, as Table C-1 clearly indicates. Each steel-laminated bearing had an outer covering of about ¼-in. of neoprene, and also about a 1/10-in.-high raised rib around the outer periphery of the compressed area. Each inner laminate of the neoprene-dacron bearings had a double thickness of dacron molded and vulcanized in; the outer surface had one layer of dacron. In bearings E-5D and E-8D, the inner dacron sheets did not remain flat and parallel near one edge, but rather curled toward the center of the bearing and stopped about ¼-in. short of reaching the outer surface.

One each of a pair of test samples was placed between the central and upper, and central and lower concrete slabs. These bearings were very carefully aligned in the center of the slabs, with the width dimension parallel to the direction of shear (as in actual installations), and the entire test set-up "squared" to assure uniform loading. The pair of bearings was then loaded at a rate of 4 percent compressive strain per minute to a compressive stress of 500 psi and held at that load for approximately 15 min to accomplish the initial compressive creep. Then, the I-beams were aligned vertically and bolted securely between the steel retaining plates on the tie-rods. The shearing was initiated by manually pumping the hydraulic jack to apply pressure to one end of the central concrete slab, and a shear strain rate of approximately 8 percent per minute was maintained with a stopwatch. At each 1/10-in. increment of shear deflection, the hydraulic pressure was read and recorded. At 50 percent shear strain, the load was maintained and the quick-release hydraulic couplings were switched; the load

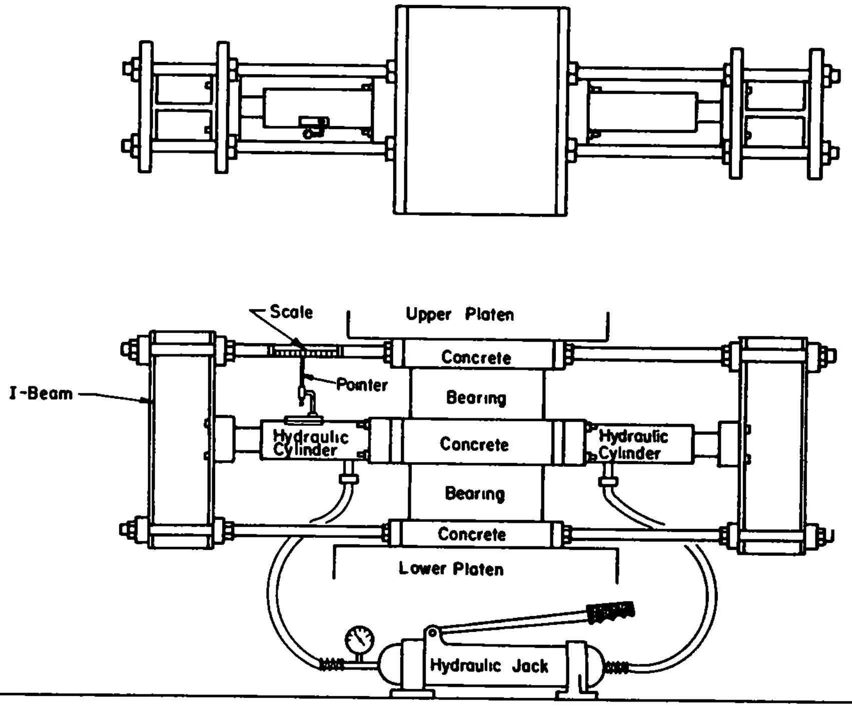


Figure C-1. Schematic of Group E test set-up.

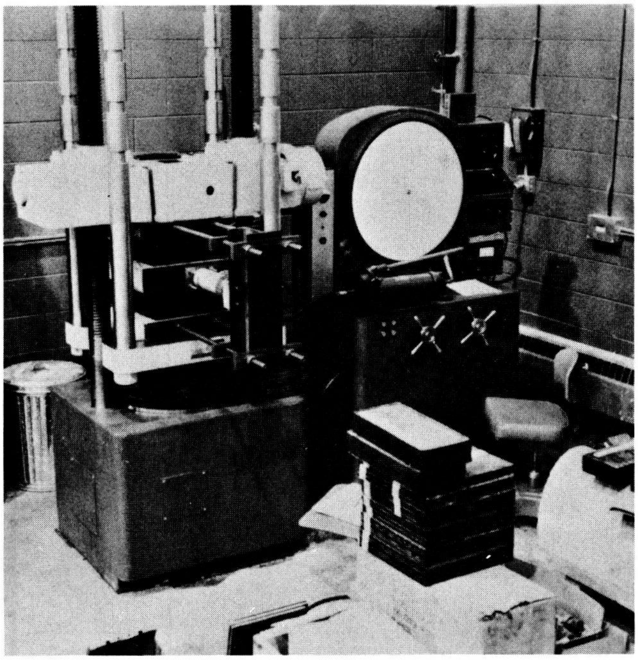


Figure C-2. Compression machine with shear rig installed.

was then allowed to drop at the same 8 percent shear strain per minute. Six load-unload cycles were accomplished in this manner, resulting in three completely reversed shear cycles. Figure C-3 shows the appearance of a large bearing (E-1S) at about 37 percent shear strain under 500 psi compressive stress. Following the shear tests, the I-beam was released and the compressive load was removed. Then, two compressive stress-strain cycles were accomplished on one bearing of each pair to 2,000 psi at a strain rate of 4 percent per minute, with continuous recording of load and deflection. All the preceding tests were run in a constant-temperature laboratory with the temperature maintained to 75 F ±1.

TABLE C-1

GROUP E EXPERIMENTAL DATA

Bearing	Width a	Length b	Thickness t	Number of Laminations n	Shape Factor S
E-1S	12.50	14.00	0.27	2	12.2
			0.45	1	7.34
			0.53	2	6.23
			0.55	3	6.00
			0.57	1	5.79
E-2S	7.00	14.00	0.26	1	8.97
			0.27	1	8.64
			0.29	2	8.05
			0.30	1	7.78
			0.31	1	7.53
E-3S	6.00	14.00	0.16	1	13.1
			0.20	1	10.5
			0.25	1	8.40
			0.27	1	7.78
			0.29	2	7.24
E-4S	6.00	18.00	0.25	1	9.00
			0.26	5	8.65
E-5D	6.00	12.25	0.25	2	8.05
			0.45	2	4.47
			0.50	1	4.03
E-6D	6.10	12.20	0.50	3	4.07
E-7D	6.00	12.00	0.50	2	4.00
E-8D	12.05	12.20	0.25	2	12.1
			0.45	2	6.74
			0.50	1	6.06
E-9D	12.00	12.00	0.50	2	6.00
	inches	inches	inches		

S = Neoprene
D = Neoprene-Dacron Combination

To investigate the possibility that the shear modulus of the neoprene material might vary through the bearing due to differing degrees of vulcanization, a 3-in. by 6-in. section was cut from the center of one bearing of each of the

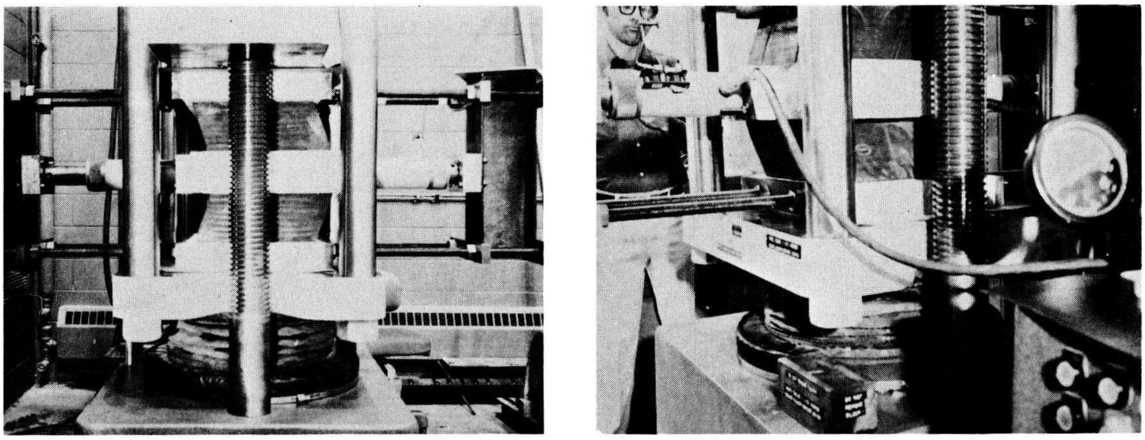


Figure C-3. Bearing E-1S under combined compression and shear.

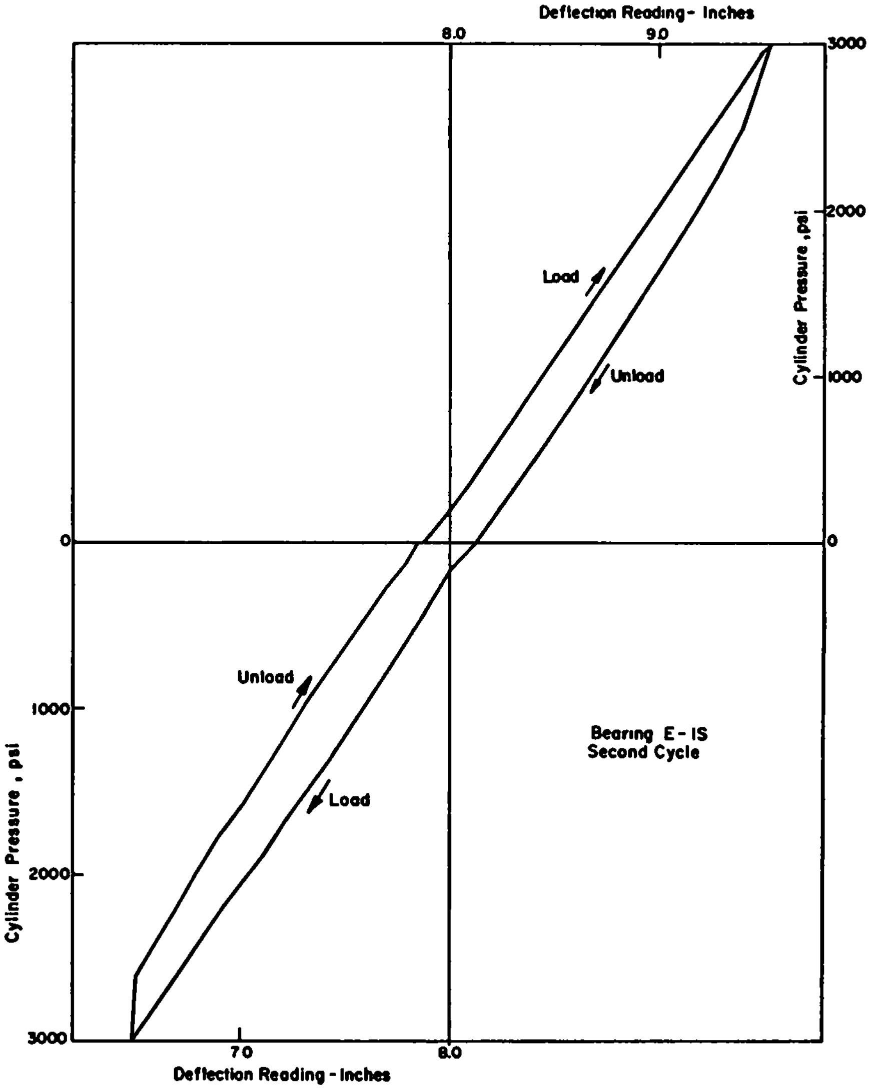


Figure C-4. Typical shear load-deflection record.

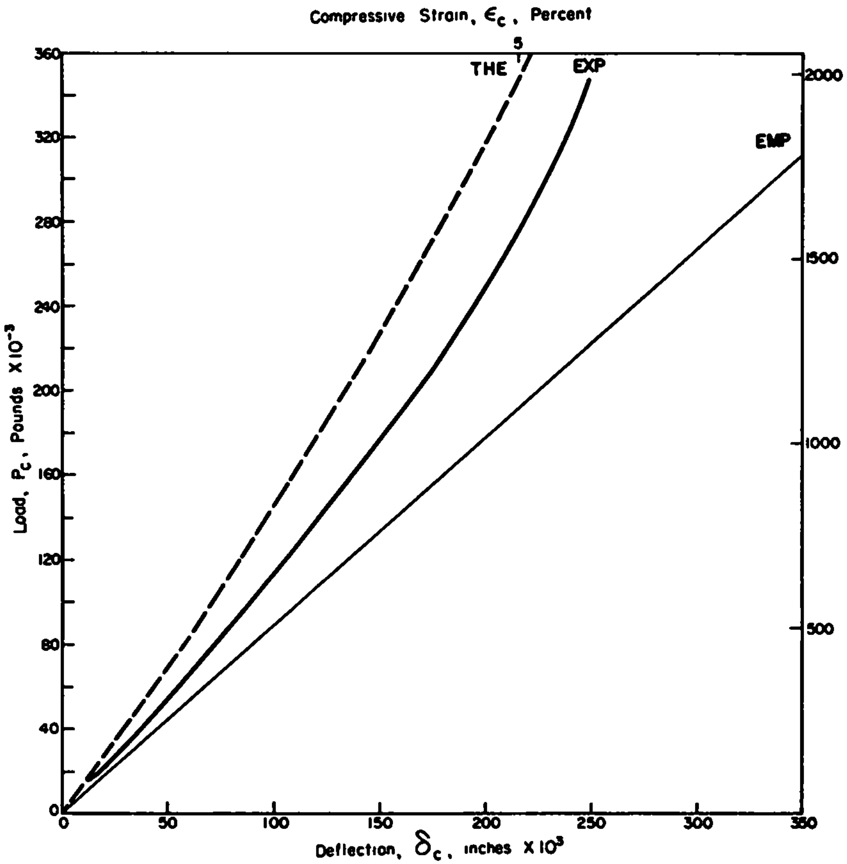


Figure C-5. Compression of bearing E-1S.

TABLE C-2

SHEAR MODULUS FOR COMMERCIAL BEARINGS

BEARING	FULL-SIZE (PSI)	3× 6 IN. (PSI)	RATIO, G_{small}/G_{full}
E-1S	118	89	0.75
E-2S	110	100	0.91
E-3S	102	102	1.00
E-4S	110	108	0.98
E-5D	112	114	1.02
E-6D	113	119	1.05
E-7D	133	134	1.01
E-8D	142	100	0.70
E-9D	160	130	0.81

nine pairs and, using the test set-up from Group A, tested in shear to 50 percent strain with four complete load-unload cycles. The same 8 percent-per-minute strain rate was used, and all tests were carried out at room temperature.

RESULTS

The data for shear load-deflection were recorded as discrete points of cylinder pressure (*CP*, psi) versus scale reading (*d*, inches) and plotted in this manner for each shear cycle (see Fig. C-4). From this curve, a slope ($= \Delta CP/\Delta d$) was calculated for each loading portion of the cycle and then factored to obtain a shear modulus. The first modulus value was disregarded as a conditioning cycle and the remaining moduli were averaged to obtain the average shear modulus (G_{avg}), as in the Group A experiments. These values are recorded in Table C-2. For each bearing, the average shear modulus together with the geometric data were used to predict the compressive stress-strain behavior by calculation with both the theoretical and empirical approaches. The experimental data for compressive load versus deflection were then put on the same plot with the predicted curves; the results are Figures C-5 through C-13. As in the Group B curves, the experimental data and theoretical curves were matched at 100 psi stress to facilitate comparison. Unfortunately, only three of the bearings had laminates of constant shape factor throughout. However, a comparison of bearings E-6D, E-7D, and E-9D (Figs. C-10, C-11, and C-12) show good correlation with the refined results of Group B (Fig. B-20).

The shear stress-strain behavior from the tests on 3- by 6-in. bearings cut from the larger commercial bearings was analyzed as in Group A, and the average shear modulus was computed from the four cycles; Table C-2 compares the modulus for the full-size bearing with that for the small sample. Bearings E-1S (3 in. by 6 in.) and E-8D (3 in. by 6 in.) were observed to shear in an "S"-shaped manner, indicative that a large part of the deflection is due to bending. This would explain two of the three low modulus ratios in Table C-2. On the other hand, E-9D (3 in. by 6 in.) can be explained only by either the effect of shearing surface (concrete versus smooth steel) or a shape factor effect. As the former would show up for all neoprene-dacron bearings, it appears that going from a shape factor of 6 to one of 2 reduced the effective shear modulus of this material by 19 percent However, a comparison of data from Group A for the same material and hardness suggests that the effects of both experimental error and variations in material composition are easily as significant as any shape factor effects. It must be concluded, then, that no discernable variations in modulus are to be found within a bearing of the sizes and shapes investigated.

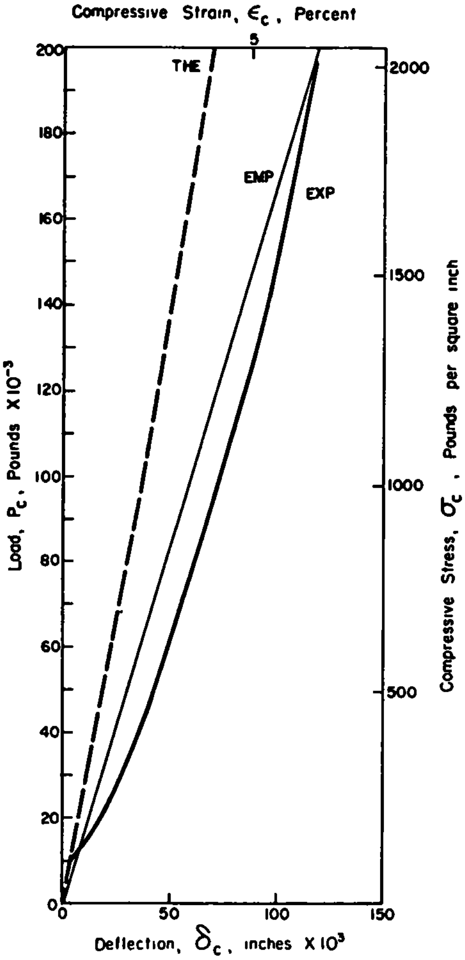


Figure C-6. Compression of bearing E-2S.

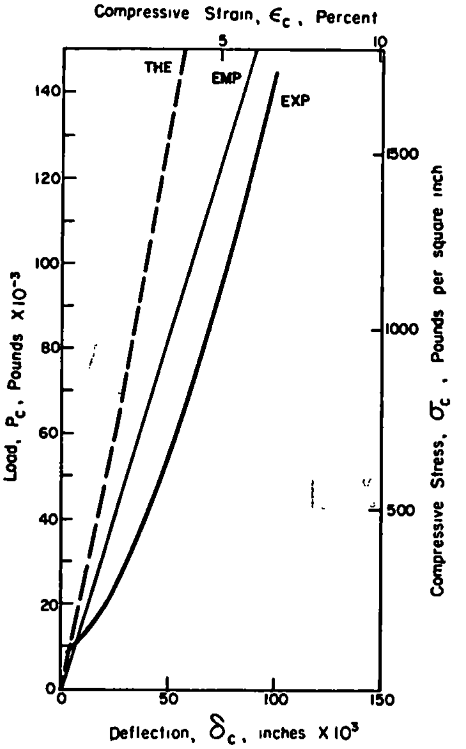


Figure C-7. Compression of bearing E-3S.

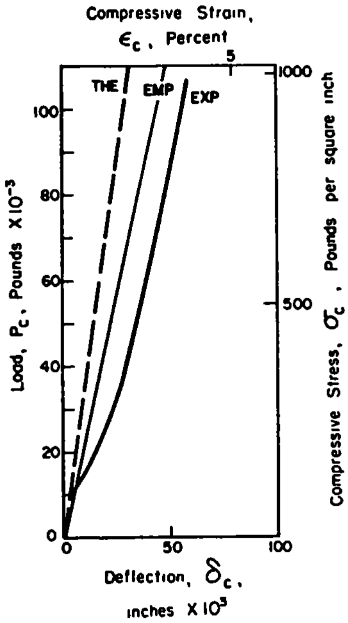


Figure C-8. Compression of bearing E-4S

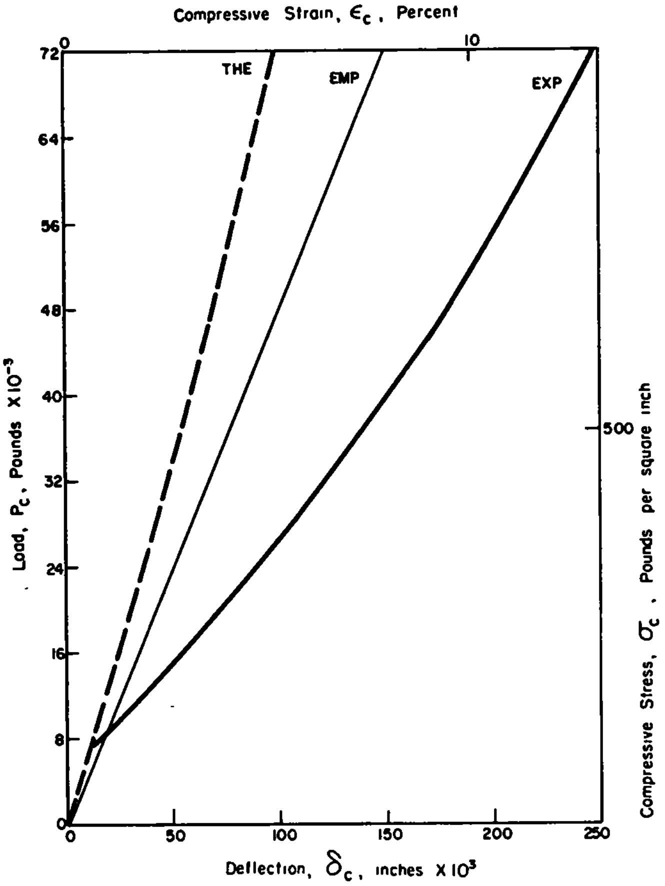


Figure C-9. Compression of bearing E-5D

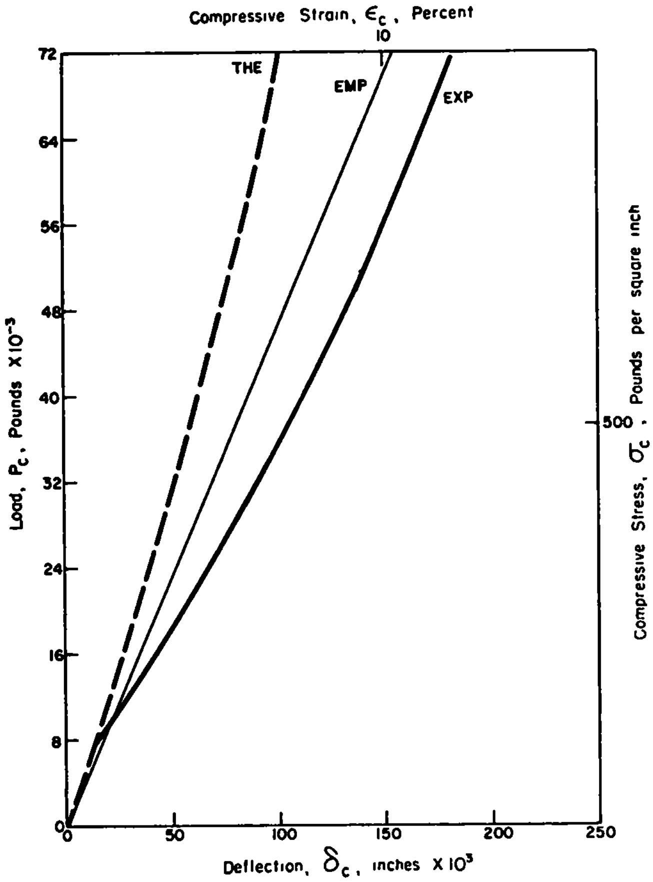


Figure C-10. Compression of bearing E-6D.

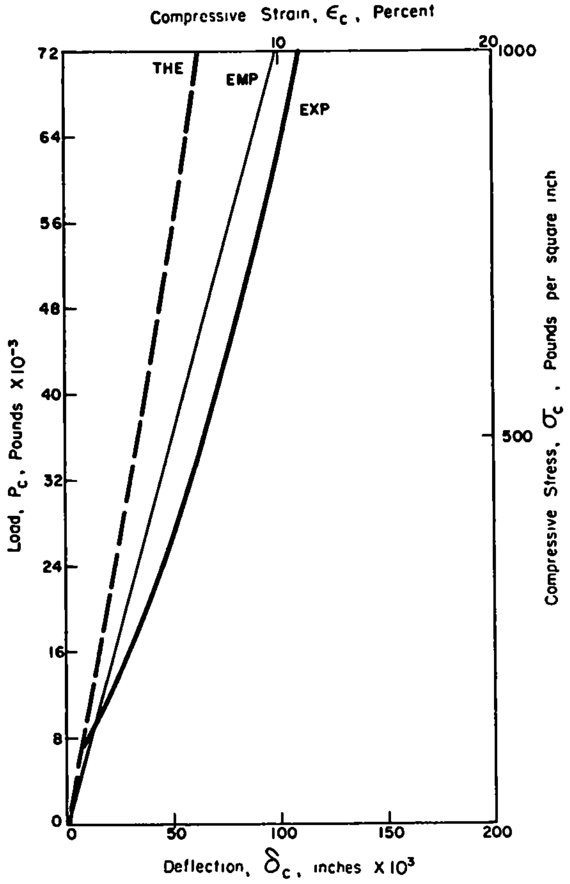


Figure C-11 Compression of bearing E-7D.

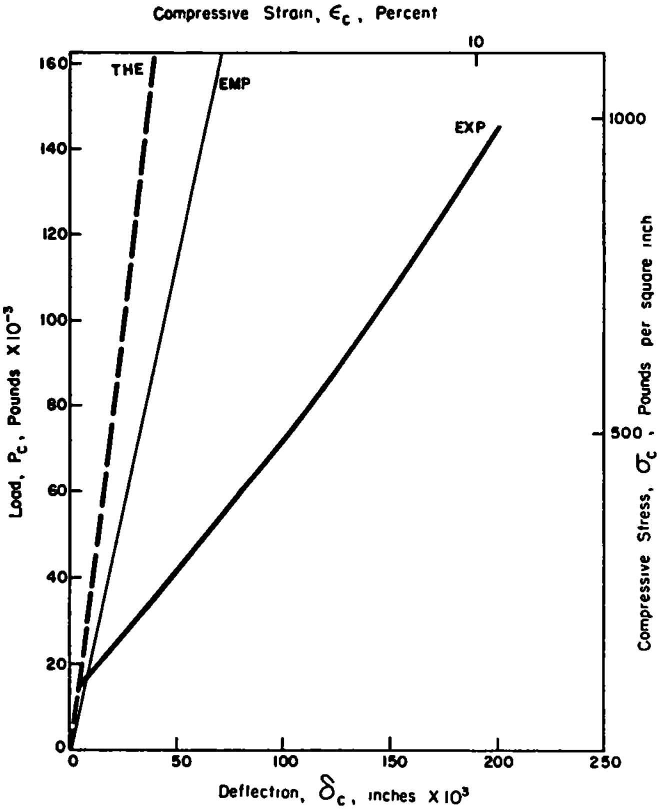


Figure C-12. Compression of bearing E-8D.

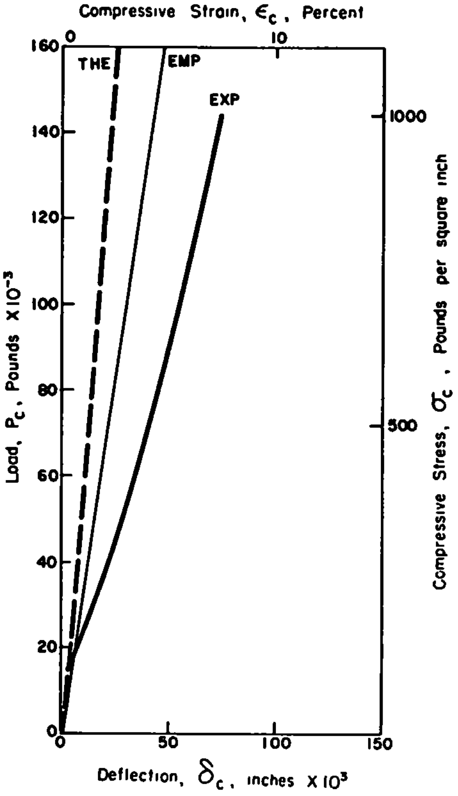


Figure C-13. Compression of bearing E-9D.

APPENDIX D

GROUP F—SHEAR CYCLING UNDER CONSTANT COMPRESSION

The Group F experiments covered the behavior of laboratory-size sample bearings under constant compressive load and high rate cycling of shear strain from +50 percent to —50 percent. The bearing materials were neoprene, natural rubber, and EPDM bonded to steel plates, and neoprene-dacron combination placed between steel plates. Hardness was nominally 50-durometer with the exception of neoprene, tested in 50-, 60-, and 70-durometer. Bearings were sheared cyclically and continuously for more than two days each to observe the effects on shear modulus and also on compressive creep.

EQUIPMENT

Several systems were used in the Group F experiments to simultaneously shear and compress each pair of samples. The entire test set-up was designed around the MTS 130-kip (dynamic capacity) hydraulic tension-compression machine located in the constant temperature and humidity laboratory. This machine was chosen, not for the capacity, but for the space it afforded the apparatus needed to hold the samples under constant compression. The MTS machine was controlled automatically in a constant-stroke mode to assure ±50 percent shear strain during the testing. Coupled to the automatic control unit was a moving-pen recorder to register load versus deflection continuously on a fixed chart paper. The horizontal and vertical pen movements were controlled by voltages proportional to shear load and deflection, respectively. The shear load was sensed by a load cell in the fixed upper machine head. The compressive loading frame was built to be mounted directly to the upper (fixed) platen of the MTS machine, as shown schematically in Figure D-1. The support yokes were originally coated on the loaded surfaces with teflon tape to allow the load frame to move freely within them; but, as the teflon deteriorated quickly, it was found that paper shims were adequate. The back

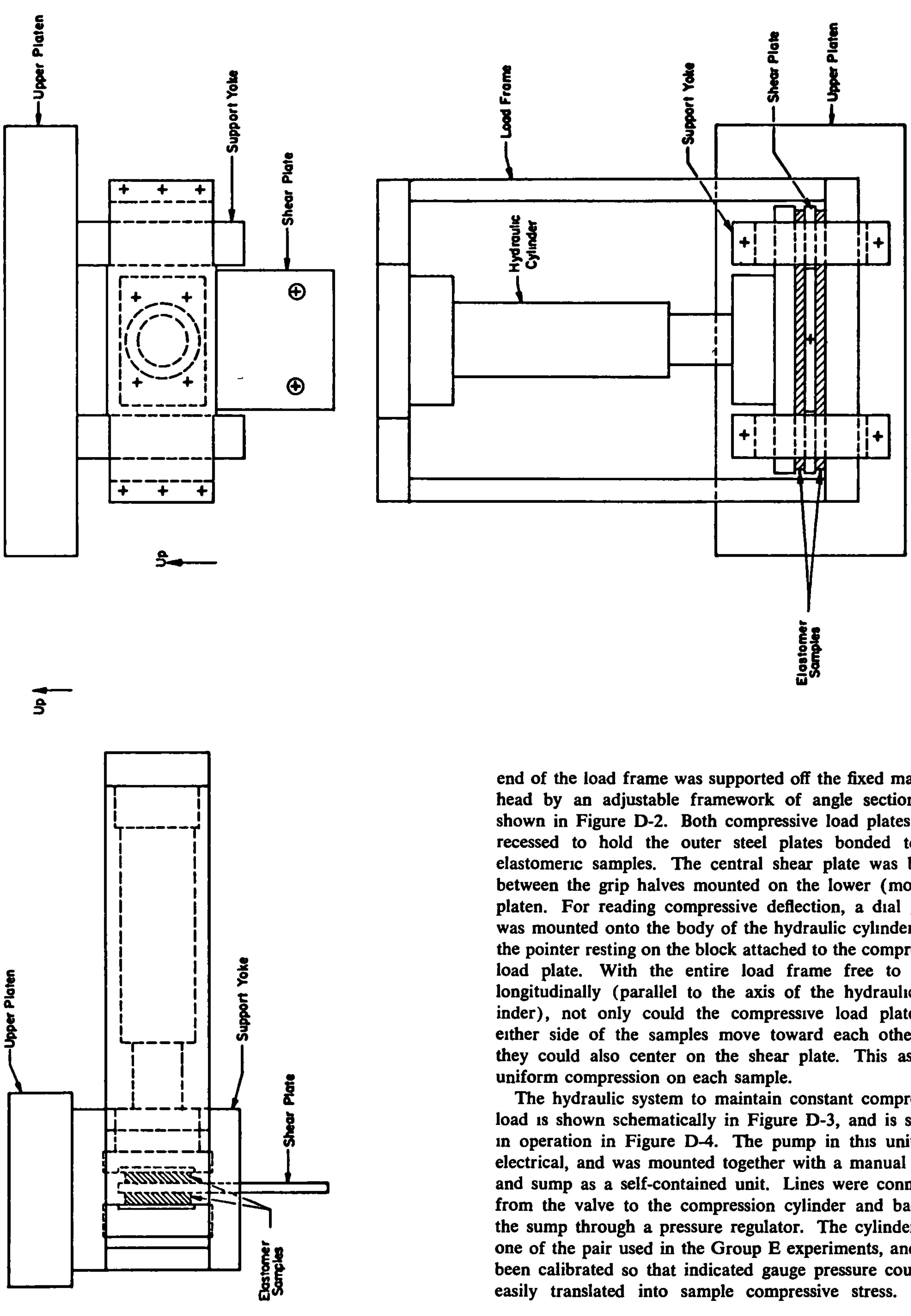


Figure D-1. Compressive loading frame.

end of the load frame was supported off the fixed machine head by an adjustable framework of angle sections, as shown in Figure D-2. Both compressive load plates were recessed to hold the outer steel plates bonded to the elastomeric samples. The central shear plate was bolted between the grip halves mounted on the lower (moving) platen. For reading compressive deflection, a dial gauge was mounted onto the body of the hydraulic cylinder with the pointer resting on the block attached to the compressive load plate. With the entire load frame free to move longitudinally (parallel to the axis of the hydraulic cylinder), not only could the compressive load plates on either side of the samples move toward each other but they could also center on the shear plate. This assured uniform compression on each sample.

The hydraulic system to maintain constant compressive load is shown schematically in Figure D-3, and is shown in operation in Figure D-4. The pump in this unit was electrical, and was mounted together with a manual valve and sump as a self-contained unit. Lines were connected from the valve to the compression cylinder and back to the sump through a pressure regulator. The cylinder was one of the pair used in the Group E experiments, and had been calibrated so that indicated gauge pressure could be easily translated into sample compressive stress. With

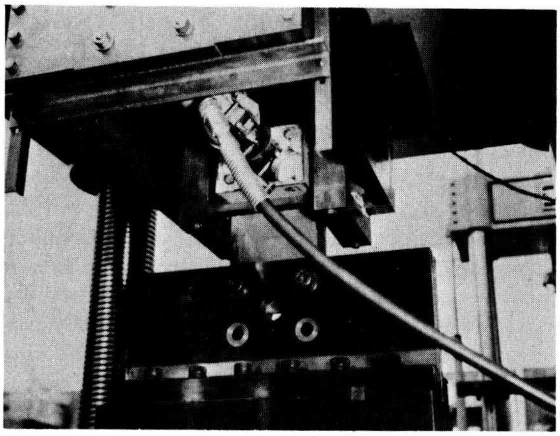
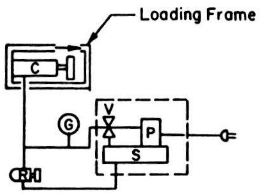


Figure D-2. Loading frame installed in MTS machine.



C = Blackhawk Hydraulic Cylinder, 20-ton capacity

R = Denison Pressure Regulator

G = Duragauge, 5000-psi capacity

V,P,S = Self-contained valve, pump, and sump, Blackhawk Enerpac rated at 6000 psi continuous

Figure D-3. Schematic of hydraulic system for maintaining constant compression.

the pump on and the valve full open, the pressure regulator could be used to set the cylinder load and maintain this load substantially constant for extended periods of time. In initial trials, it was found that the hydraulic fluid tended to run at excessively high temperatures, so a water-bath heat sink was constructed around the sump; this proved adequate in reducing operating temperatures to a reasonable level.

METHOD

Test samples were cut from the appropriate sheet stock of neoprene, natural rubber, EPDM, and neoprene-dacron. Samples were all of either ¼- or ½-in. nominal thickness and, with the exception of neoprene, were all of nominally 50-durometer hardness. As indicated in Table D-1, neoprene samples were fabricated from 60- and 70-durometer material. With the exception of the neoprene-dacron, all samples were bonded in a "sandwich" consisting of two similar pieces mounted on either side of a ½-in.-thick central steel shear plate, with ¼-in. steel outer plates. The bonding method is described in Appendix E. The neoprene-dacron samples were placed, rather than bonded, between the steel plates.

The pump unit was started several minutes prior to test initiation to assure that a constant-temperature condition had been reached in the hydraulic fluid. The completed bearing was then placed between the compression load plates and a small load was applied to hold the bearing. The entire load frame assembly was squared and moved manually to assure complete freedom in the longitudinal direction. Next, the lower grip halves were moved up and the shear plate was bolted between them; the apparatus was carefully watched to make sure that no shear load was placed on the bearing. The dial gauge was moved into position and a zero reading was taken, together with the reading on the pressure gauge. The sample was then loaded in compression at approximately 4 percent strain per minute, until a compressive stress of 500 psi was reached. At increments of loading, both load and deflection were recorded. When 500 psi was reached, the time

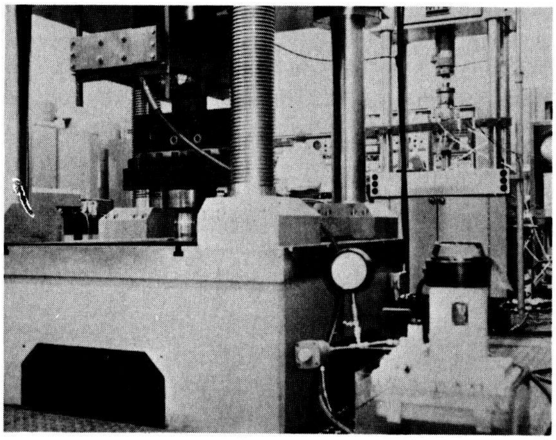


Figure D-4. Hydraulic system in operation, with loading frame.

TABLE D-1

GROUP F EXPERIMENTAL DATA

Bearing	Width a	Length b	Thickness t	Shape Factor S	Hardness	Compressive Creep (1)
F-1S	3.01	6.03	0.51	1.97	51	15
F-1D	3.04	5.98	0.50	2.02	57	47
F-1N	3.05	6.00	0.50	2.02	47	14
F-1E	3.02	5.69	0.50	1.98	53	--
F-2S	2.93	6.29	0.54	1.87	60	20
F-3S	3.02	5.99	0.52	1.93	70	73
F-4S	3.02	6.05	0.27	3.73	51	30
F-4N	3.02	6.04	0.30	3.35	47	21
F-4E	3.01	5.98	0.32	3.18	53	25
F-5S	3.01	12.10	0.50	2.41	51	38
F-5D	2.92	11.96	0.50	2.41	57	41
F-5N	3.00	11.98	0.46	2.59	47	38
F-5E	2.98	11.98	0.50	2.37	53	32
	inches	inches	inches		Shore A Durometer	percent

(1) After 10^5 cycles.

S = Neoprene
D = Neoprene-Dacron Combination
N = Natural Rubber
E = EPDM

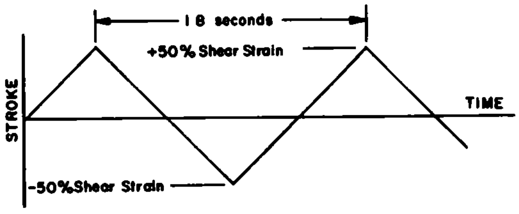


Figure D-5. Shear loading function.

was noted and the shear cycling was begun. The automatic control on the shear ram was set to give a ramp function of stroke versus time, as shown in Figure D-5. In this manner, 100,000 completely reversed shear cycles were accomplished in approximately 50 hr. At intervals of time (and number of cycles), a shear load-deflection trace was recorded and the dial gauge was read for compressive deflection. Also, the appearance of the bearing was observed and any tendency for the bearing to heat up was noted. At the end of cycling, the shear and compression loads were released, the bearing was removed, and any deterioration of the elastomer or the bond was noted

RESULTS

The cylinder pressure versus dial gauge readings during initial compression of each sample were reduced to a tabulation of data points representing compressive stress-strain behavior. For the bearings where this information was recorded, Figures D-6 through D-11 show the compressive behavior compared to that predicted by both the theoretical and empirical approaches. As in the Group B analysis, the experimental curve was shifted to agree with the theoretical curve at a compressive stress of 100 psi. Comparison of these curves with those in Group B shows a general agreement in that, with the exception of bearing F-4S, the experimental curve of compressive stress versus strain lies somewhere between the two predicted curves for shape factors between 2 and 4.

Compressive creep was analyzed next, with creep versus time (or number of cycles) the area of interest. Creep is defined as:

$$\text{Creep} = \left(\frac{\text{deflection at time } t}{\text{initial deflection}} - 1 \right) \times 100 \text{ (percent)} \tag{D-1}$$

For each material, these data were plotted on a graph and a curve was drawn through the data points. Figures D-12

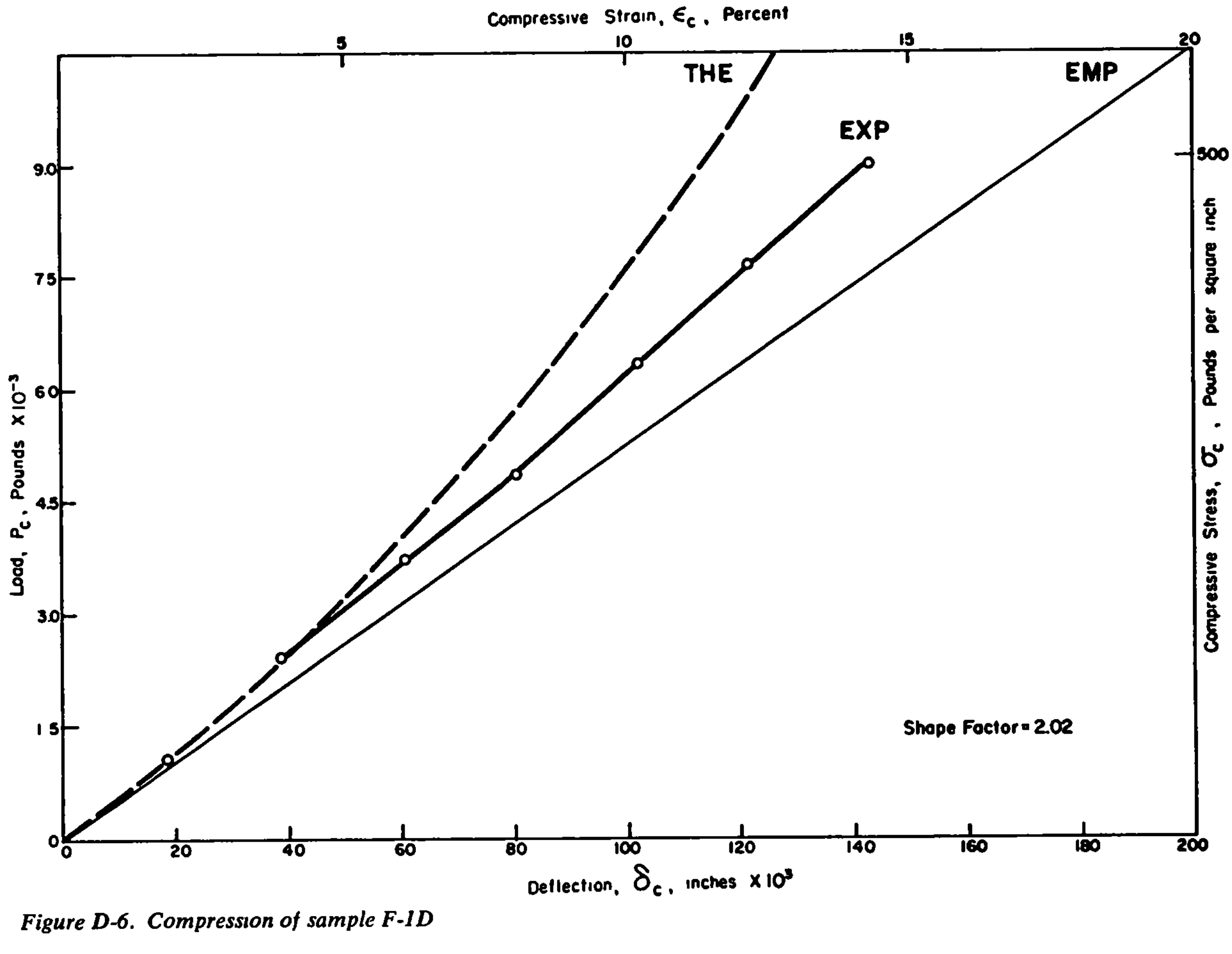


Figure D-6. Compression of sample F-1D

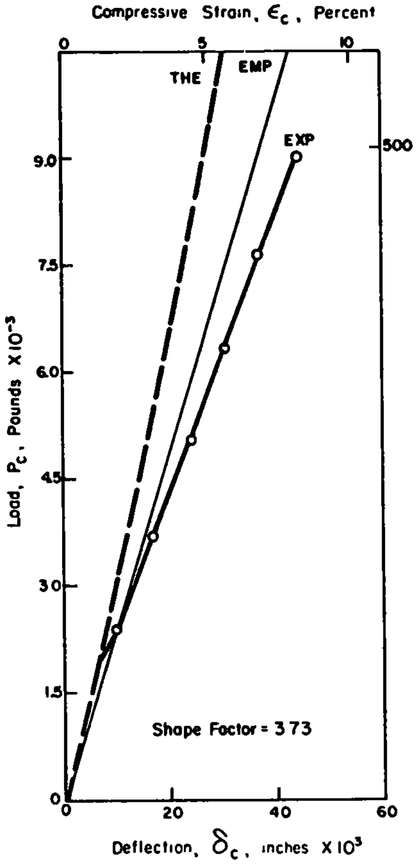


Figure D-7. Compression of sample F-4S.

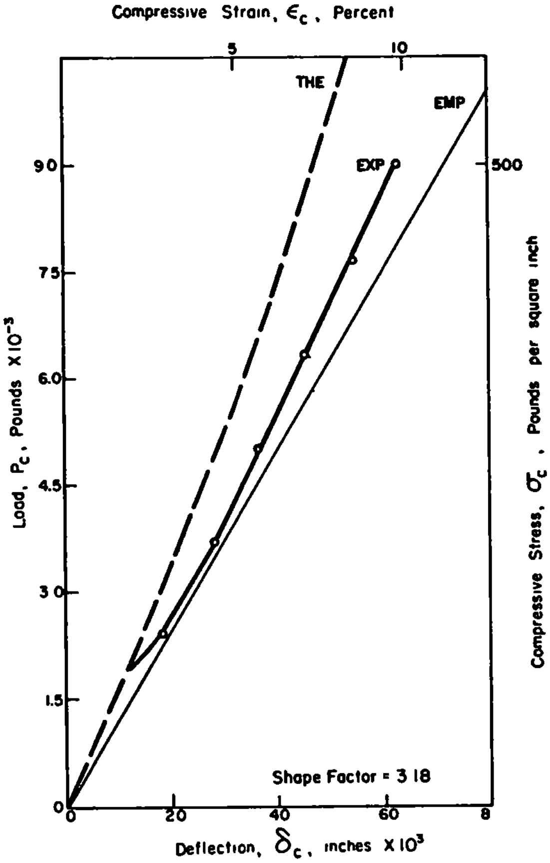


Figure D-8 Compression of sample F-4E

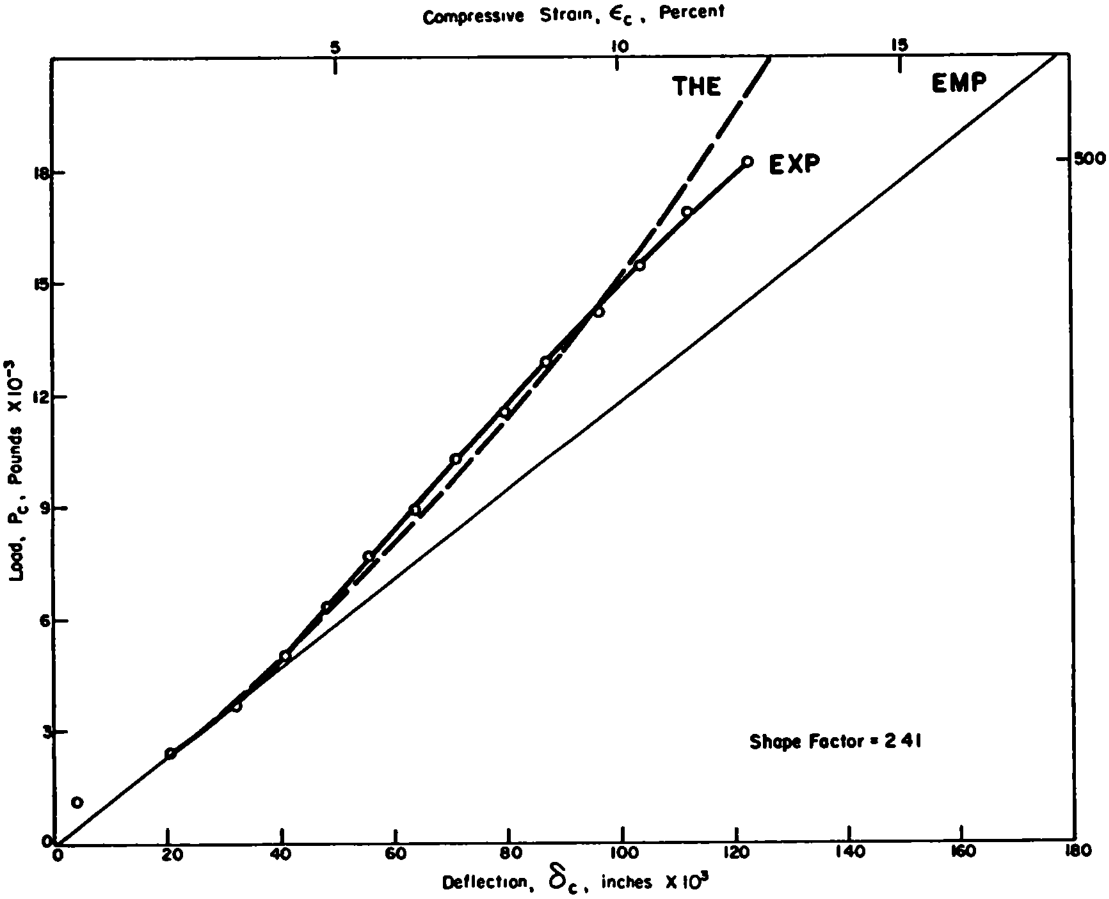


Figure D-9. Compression of sample F-5S.

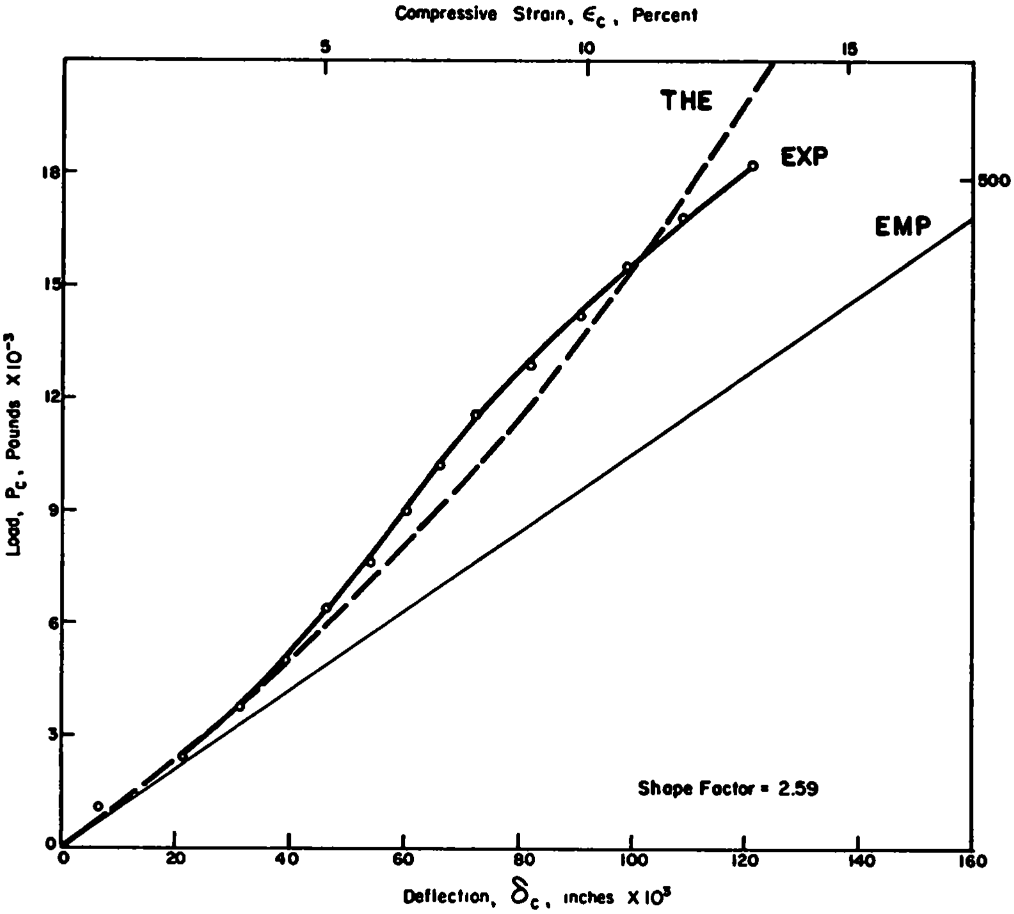


Figure D-10. Compression of sample F-5N.

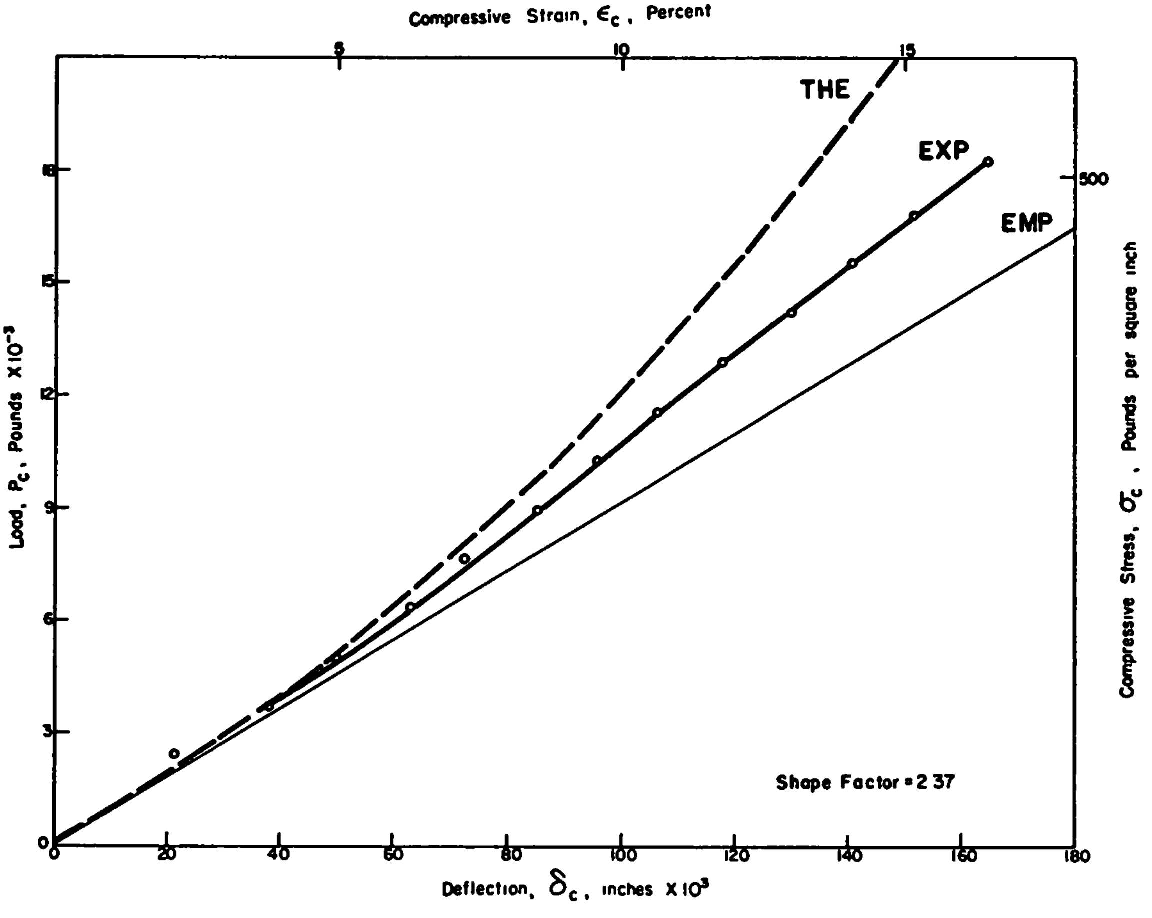


Figure D-11. Compression of sample F-5E

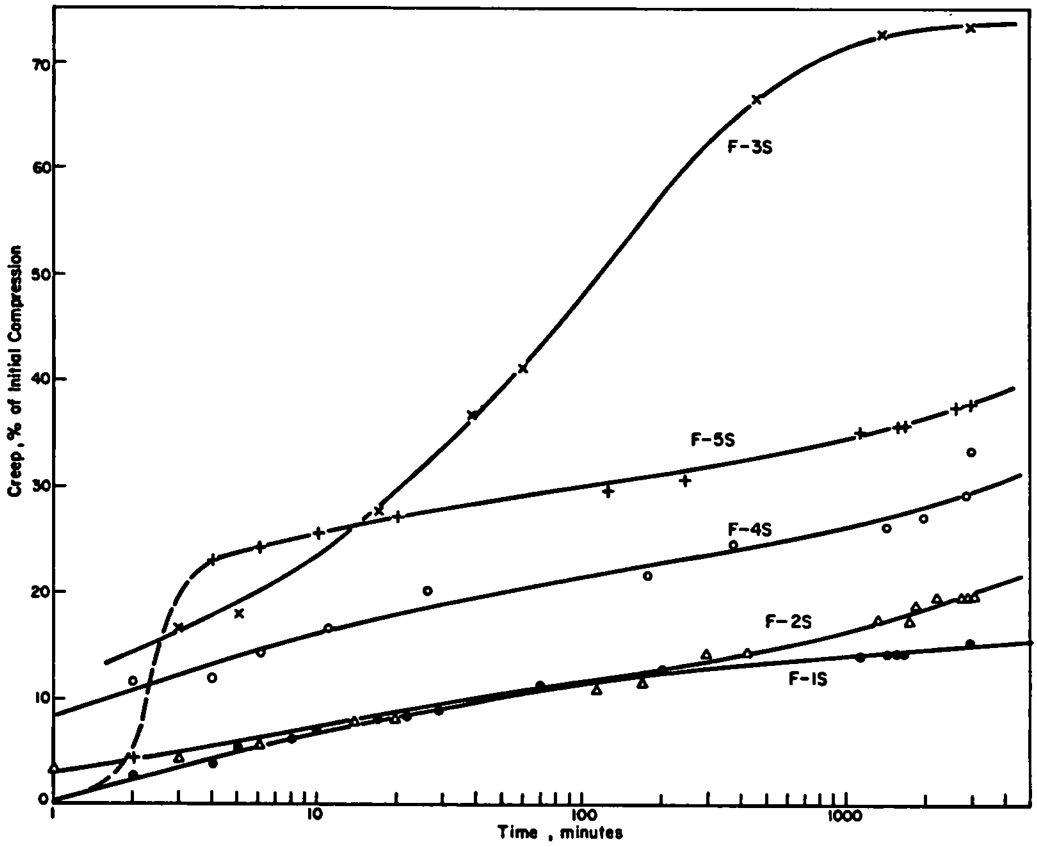


Figure D-12. Creep in compression—neoprene.

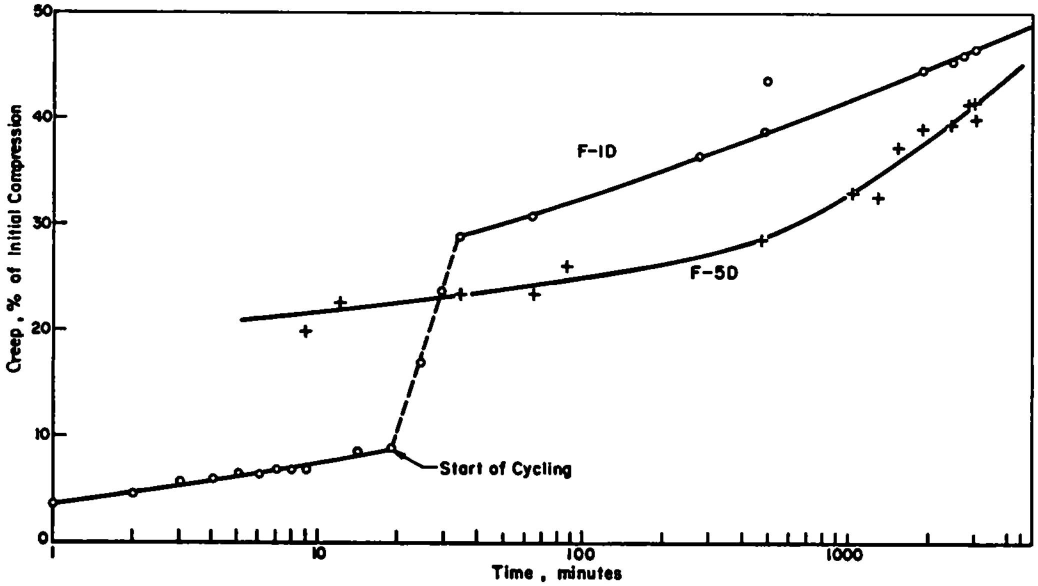


Figure D-13 Creep in compression—neoprene-dacron

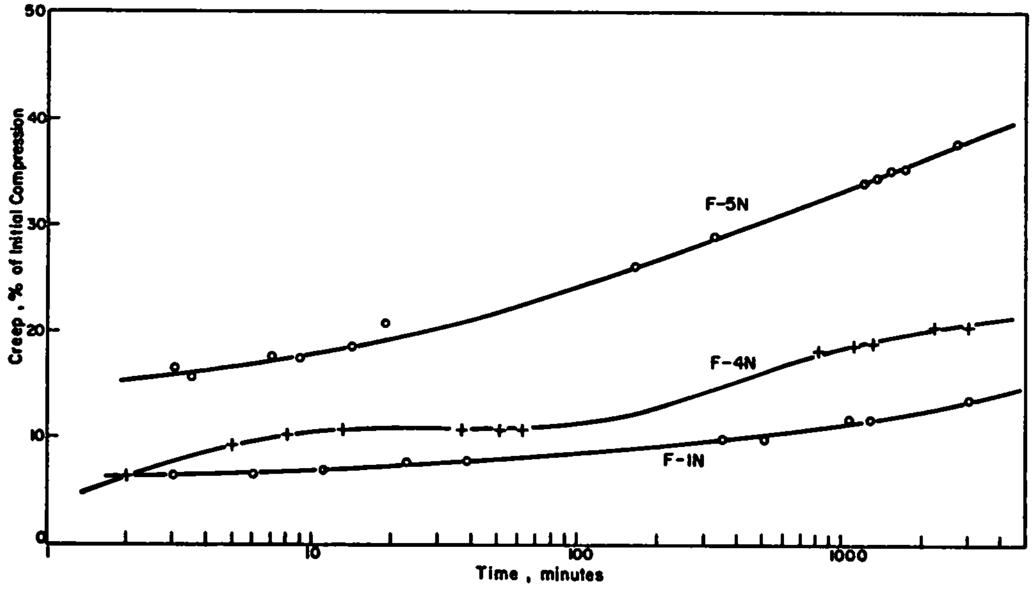


Figure D-14. Creep in compression—natural rubber

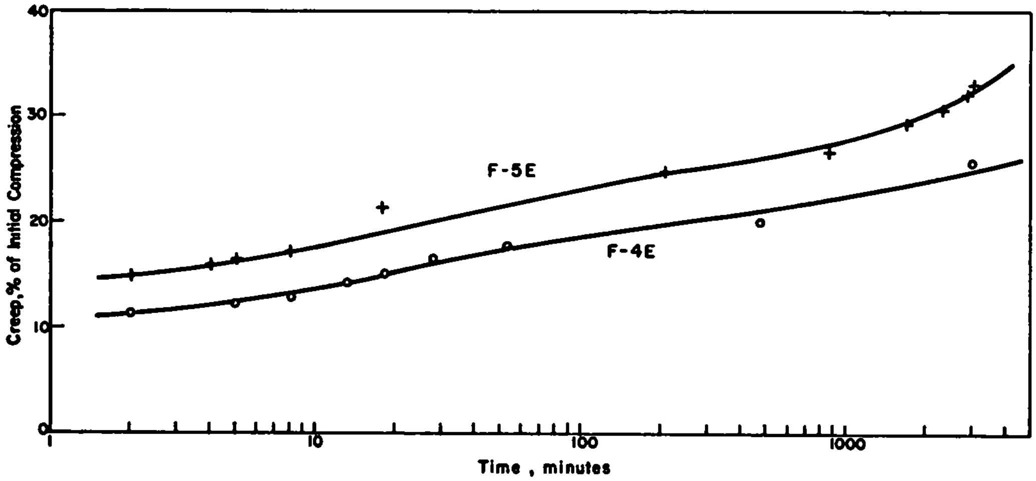


Figure D-15. Creep in compression—EPDM.

through D-15 are the results; it was determined that, because of total bond failure and a possibly slipping dial gauge, the data for bearing F-1E would be discarded.

Except for bearing F-1E, bonding was not a problem in this series. Although three other bearings exhibited some edge bond failure, this was judged inconsequential because a large fillet of bond was built onto the edge and the bulging of the bearing under compression in several cases caused this bond to split. Only one bearing, F-5N, showed any damage to the elastomer; the nature of this damage was small bits of rubber being "rubbed" off the sample by the combined shearing and compression of one exposed surface on the raised bond fillet. This probably was a case of the fillet doing damage, because the bonding was all done by hand. During the cycling, only one bearing, F-1D, showed any signs of becoming warm to touch and, even in this bearing, the effect was not judged significant in view of the large shear strain and high shear rate.

The effect of cycling on shear modulus was investigated by measuring the slope of the loading portion of the shear load-deflection plot and tabulating these data versus the number of cycles through which the bearing had been sheared. For the convenience of comparison, the data were plotted for three different hardnesses, represented by bearings F-1S, F-2S, and F-3S, on a single graph of shear modulus versus the logarithm of the number of cycles (Fig. D-16). Then, on the same scales, the data from the other bearings were plotted by shape factor (Figs. D-17, D-18, and D-19). Change in shear modulus from 10^2 to 10^5 cycles is compared in Table D-2.

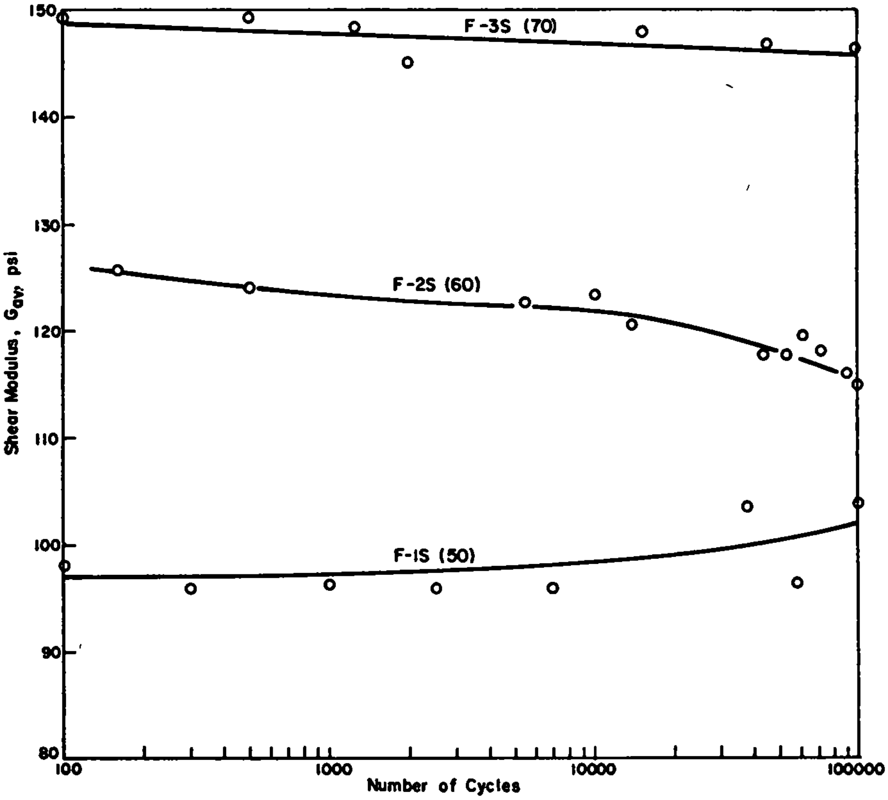


Figure D-16 Hardness comparison—shear modulus versus number of cycles

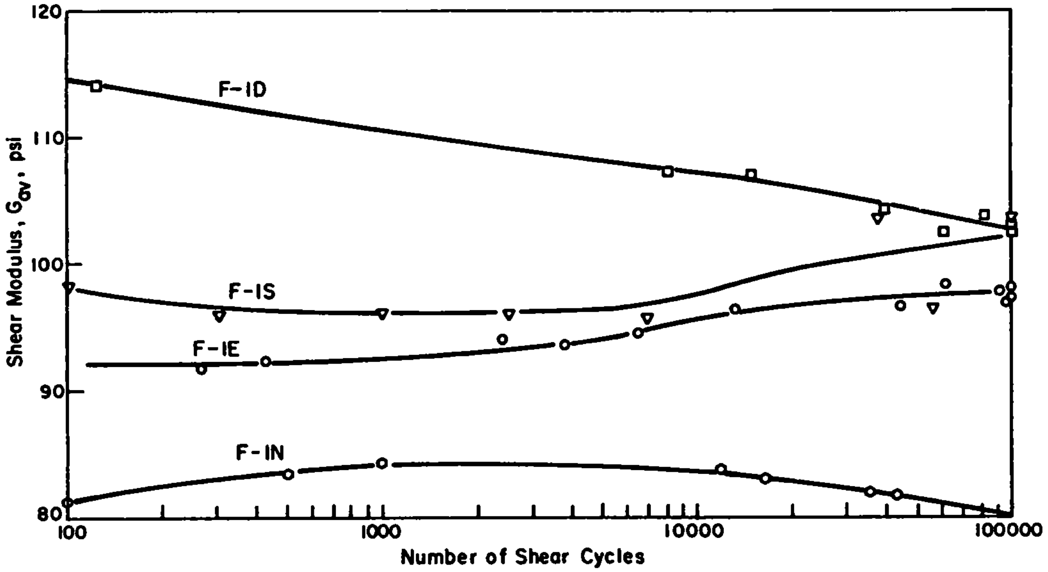


Figure D-17. Material comparison—shear modulus versus number of cycles (S=2.0).

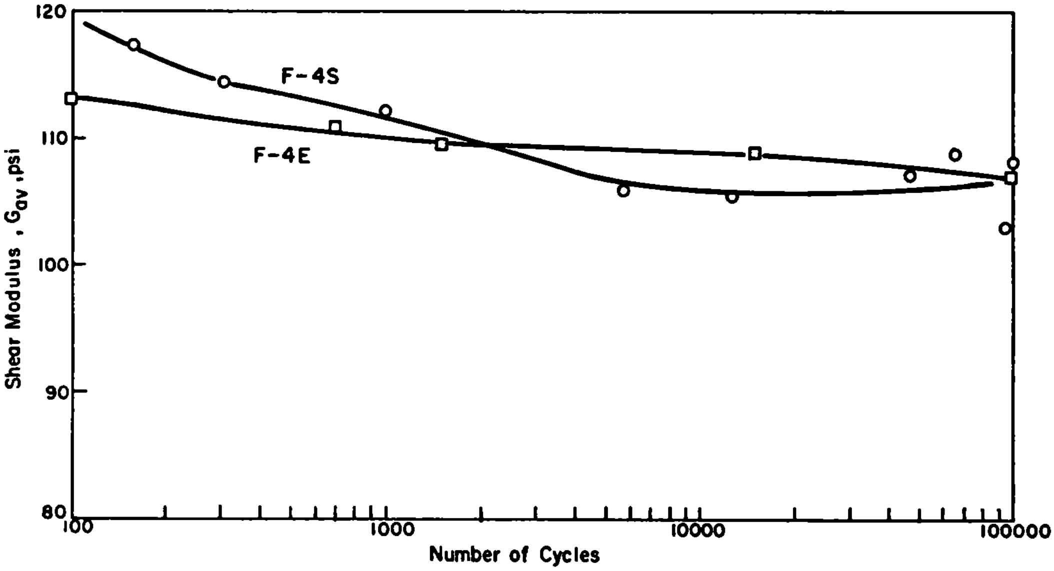


Figure D-18. Material comparison—shear modulus versus number of cycles (S=*4.0*).

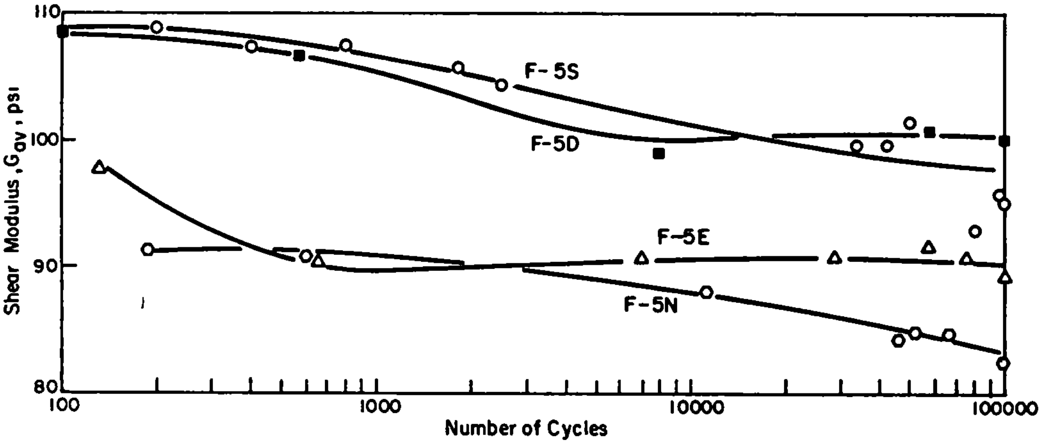


Figure D-19. Material comparison—shear modulus versus number of cycles (S=*2.4*).

TABLE D-2

CHANGE IN SHEAR MODULUS WITH CYCLING

BEARING	SHEAR MODULUS (PSI) AT: 10^2 CYCLES	10^5 CYCLES	PERCENT CHANGE
F-1S	98	104	+6
F-2S	126	115	−9
F-3S	149	147	−1
F-1D	114	102	−11
F-1N	81	80	−1
F-1E	93	98	+5
F-4S	119	108	−9
F-4N	140	127	−9
F-4E	113	107	−5
F-5S	108	100	−7
F-5D	109	95	−13
F-5N	92	82	−11
F-5E	99	89	−10
Average	—	—	−6

APPENDIX E

BONDING OF ELASTOMERIC SAMPLES TO STEEL PLATES

The procedure for bonding bearing pad samples for use in experimental Groups A, B, and F uses "Scotchweld" brand adhesive manufactured by the 3M Company. The product number is EC2216 and the adhesive is a two-component system consisting of a base and an accelerator hardener. The steps are as follows:

1. Step One: Sandblast steel plates, both sides, to assure a good bonding surface and also to remove warping stresses from plates.
2. Step Two: Clean elastomer, and sand lightly to remove any residual mold release agent.
3. Step Three: Wipe both plates and elastomer with a cloth soaked in toluene to remove any grease or dirt.
4. Step Four: Mix adhesive according to instructions and allow to sit for approximately 20 min. (Weight ratio is 5 parts B to 7 parts A.)
5. Step Five: Spread adhesive on plates and elastomer with the aid of a "doctor" blade (7.5 mils × desired width) and allow to sit for 10 to 30 min, depending on the dryness of the adhesive.
6. Step Six: Assemble bearing pad sample and block to prevent lateral movement. Assembled bearing must be level to prevent elastomer from tending to slide out.

APPENDIX F

PREDICTION OF COMPRESSIVE BEARING BEHAVIOR

EMPIRICAL (2)

An empirical approach to the prediction of elastomeric bearing compressive behavior exists using the concept of shape factor (S). The shape factor of a bearing is defined as one loaded area divided by the total free area. For a fully bonded rectangular bearing, the shape factor is:

$$S = \frac{ab}{2t\,(a+b)} \qquad \text{(F-1)}$$

in which

a = width, inches;
b = length, inches; and
t = original thickness, inches.

A compression modulus, E_c, is defined depending upon the shape factor:

$$E_c = E_o\,(1 + 2kS^2) \qquad \text{(F-2)}$$

in which

E_o = Young's modulus; and
k = empirically derived constant, depending on shear modulus.

For compressive strain ϵ_c, then, one has the relation from Hooke's Law:

$$\epsilon_c = \frac{\sigma_c}{E_c} = \frac{\sigma_c}{E_o\,(1 + 2kS^2)} + \frac{\sigma_c}{E_\infty} \qquad \text{(F-3)}$$

in which

σ_c = average compressive stress, psi; and
E_∞ = bulk compression modulus, psi. (The final term is the strain due to bulk compression.)

The stress may be defined as the compressive load divided by the loaded area, and the strain may be defined as the compressive deflection divided by the original thickness. When this is done, the entire expression may be rearranged to define a compressive stiffness, such that:

$$\text{Stiffness}_c = \frac{\delta_c}{P_c} = \frac{t}{AE_o\,(1 + 2kS^2)} + \frac{t}{AE_\infty} \qquad \text{(F-4)}$$

in which

δ_c = compressive deflection, inches;
P_c = compressive load, pounds; and
$A = (a)(b)$ = loaded area, square inches.

Figure F-1 shows the curves of shear modulus (G) versus empirical constant (k), Young's modulus (E_o), and bulk compression modulus (E_∞) that were used together with geometric data to predict the compressive stiffness of bearings in Groups B, E, and F. For multilaminate bearings, the compressive stiffness from Eq. F-4

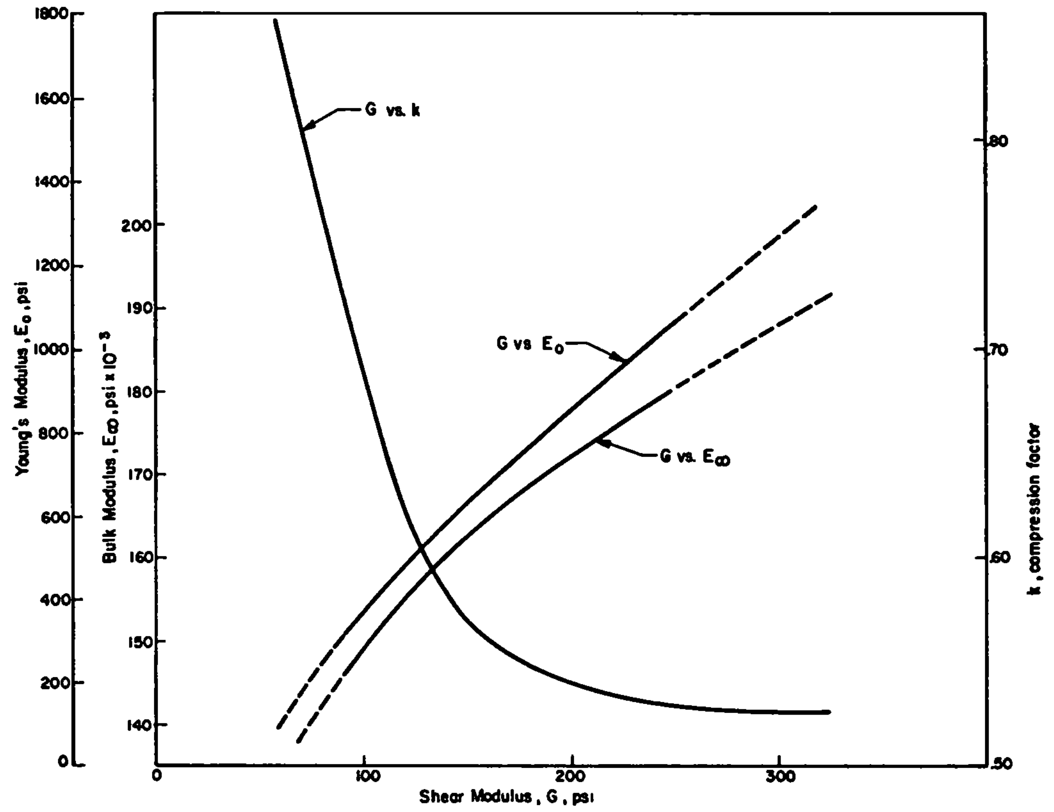


Figure F-1. Variation in material properties with shear modulus—empirical.

is multiplied by the number of laminations. Where several laminations of differing thickness and shape factor are involved (as in Group E), the stiffness values for each laminate are added.

THEORETICAL (4)(5)

A purely theoretical approach to the prediction of elastomeric bearing compressive behavior exists, with the basic parameters being the material property of shear modulus (G) and the nondimensional geometric parameters of length-to-width ratio (b/a) and width-to-thickness ratio (a/t). The theory states that the compressive load-deflection behavior of a bonded rectangular elastomeric bearing is described by the following:

$$\sigma_c = \frac{P_c}{ab} = \frac{G}{C_t} a^2 \frac{\Delta t}{(t - \Delta t)^3} \tag{F-5}$$

or, rearranging,

$$\epsilon_c = \frac{\Delta t}{t} = \left[\frac{1}{2} + \frac{G}{6\sigma_c C_t}\left(\frac{a}{t}\right)^2\right] - \left\{\left[\frac{1}{2} + \frac{G}{6\sigma_c C_t}\left(\frac{a}{t}\right)^2\right]^2 - \frac{1}{3}\right\}^{1/2} \tag{F-6}$$

in which

P_c = compressive load, pounds,
a = width, inches;
b = length, inches;
σ_c = average compressive stress, psi;
G = shear modulus, psi;
t = original thickness, inches;
Δt = compressive deflection, inches; and
C_t = coefficient, the value of a complex algebraic term, a function of only (b/a).

The value of the coefficient, C_t, is not empirically derived, but rather is the result of a purely theoretical expression:

$$C_t = \frac{\pi^4}{96 \sum_{n=1,3,5}^{n=\infty} \frac{1}{n^4}\left[1 - \frac{2}{n\pi}\frac{a}{b}\tan\mathrm{h}\frac{n\pi b}{2a}\right]} \tag{F-7}$$

The value of C_t has been calculated for a range of length-to-width ratios and plotted as shown in Figure F-2.

It is important to note that these expressions may also be used to predict the compressive behavior of multilaminate bearings by multiplying the resulting compressive deflection (or strain) by the number of equal laminates. Laminates of various thicknesses require separate calculations for each laminate and the addition of each of the resulting predicted deflections.

Because of their nature, the foregoing expressions were programmed in FORTRAN to be evaluated by the CDC 6400 digital computer. This program was used in the prediction of compressive load-deflection behavior for bearings in Groups B, E, and F, and is shown in Figure F-3. The plot subroutine in this program allows the calculated values to be plotted automatically, facilitating the comparison with the experimental data. A sample of output, together with the plotted values, is shown in Figure F-4.

Graph of Equation :

$$C_t = \frac{\pi^4}{96\sum\limits_{n=1,3,5\ldots}^{n=\infty} \frac{1}{n^4}\left[1 - \frac{2}{n\pi}\frac{a}{b}\tanh\frac{n\pi b}{2a}\right]}$$

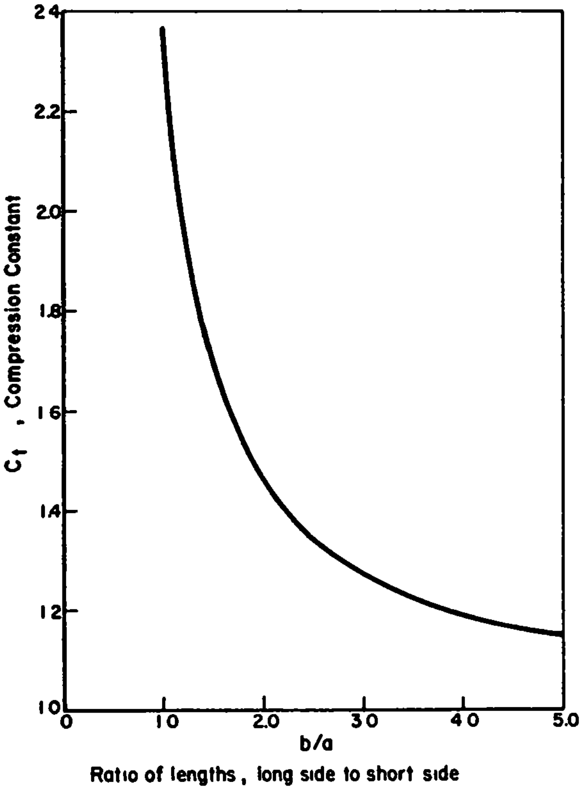
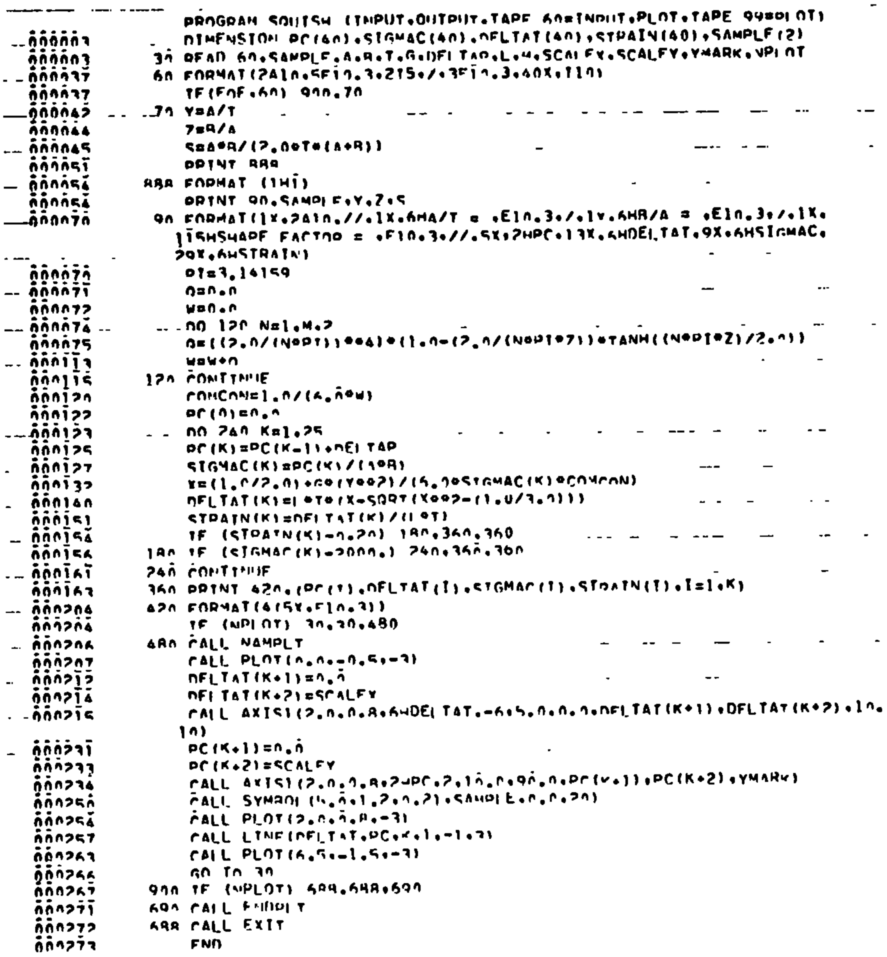
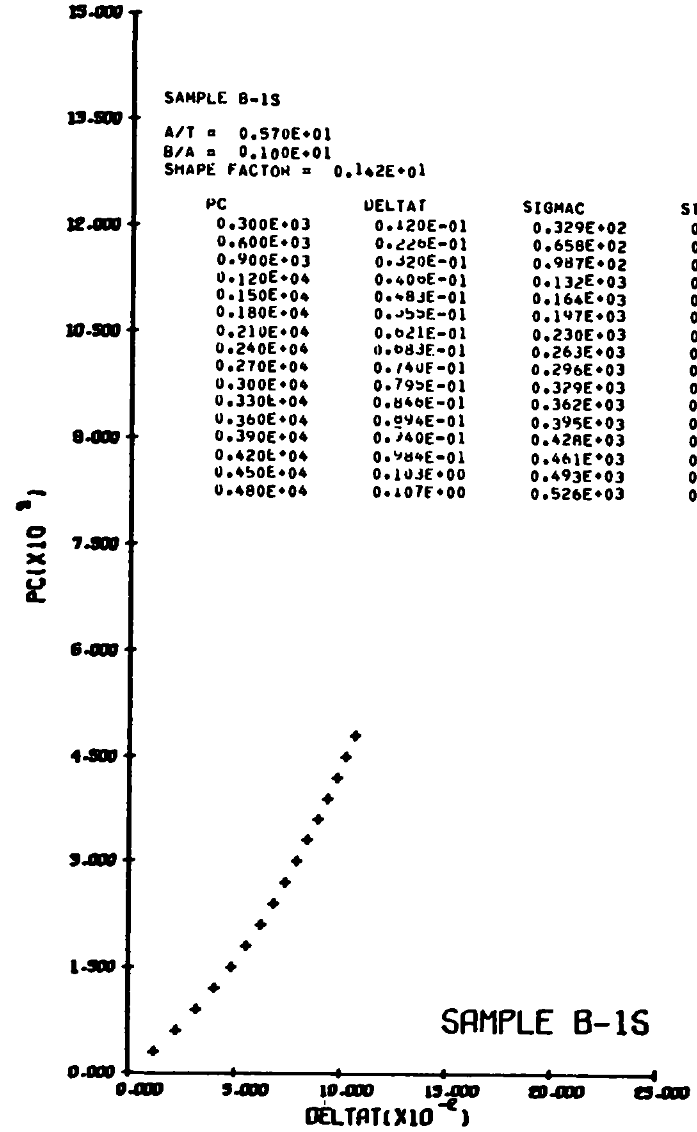


Figure F-2. Compression constant; theoretical approach.



```
                     PROGRAM SQUISH (INPUT,OUTPUT,TAPE 60=INPUT,PLOT,TAPE 99=PLOT)
  000003             DIMENSION PC(60),SIGMAC(40),DELTAT(40),STRAIN(40),SAMPLE(2)
  000003          30 READ 60,SAMPLE,A,B,T,G,DELTAP,L,M,SCALEX,SCALEY,YMARK,NPLOT
  000037          60 FORMAT(2A10,5F10.3,2I5,/,3F10.3,40X,I10)
  000037             IF(EOF,60) 990,70
  000042          70 Y=A/T
  000044             Z=B/A
  000045             S=A*B/(2.0*T*(A+B))
  000051             PRINT 888
  000054         888 FORMAT (1H1)
  000054             PRINT 90,SAMPLE,Y,Z,S
  000070          90 FORMAT(1X,2A10,//,1X,6HA/T = ,E10.3,/,1X,6HB/A = ,E10.3,/,1X,
                    115HSHAPE FACTOR = ,F10.3,//,5X,2HPC,13X,6HDELTAT,9X,6HSIGMAC,
                    29X,6HSTRAIN)
  000070             PI=3.14159
  000071             Q=0.0
  000072             W=0.0
  000074             DO 120 N=1,M,2
  000075             Q=((2.0/(N*PI))**4)*(1.0-(2.0/(N*PI*Z))*TANH((N*PI*Z)/2.0))
  000113             W=W+Q
  000115         120 CONTINUE
  000120             COMCON=1.0/(6.0*W)
  000122             PC(0)=0.0
  000123             DO 240 K=1,25
  000125             PC(K)=PC(K-1)+DELTAP
  000127             SIGMAC(K)=PC(K)/(L*B)
  000132             X=(1.0/2.0)+G*(Y**2)/(5.0*SIGMAC(K)*COMCON)
  000140             DELTAT(K)=L*T*(X-SQRT(X**2-(1.0/3.0)))
  000151             STRAIN(K)=DELTAT(K)/(L*T)
  000154             IF (STRAIN(K)-0.20) 180,360,360
  000156         180 IF (SIGMAC(K)-2000.) 240,360,360
  000161         240 CONTINUE
  000163         360 PRINT 420,(PC(I),DELTAT(I),SIGMAC(I),STRAIN(I),I=1,K)
  000204         420 FORMAT(4(5X,F10.3))
  000204             IF (NPLOT) 30,30,480
  000206         480 CALL NAMPLT
  000207             CALL PLOT(0.0,-0.5,-3)
  000212             DELTAT(K+1)=0.0
  000214             DELTAT(K+2)=SCALEX
  000215             CALL AXIS1(2.0,0.8,6HDELTAT,-6,5.0,0.0,DELTAT(K+1),DELTAT(K+2),10.,
                    10)
  000231             PC(K+1)=0.0
  000233             PC(K+2)=SCALEY
  000234             CALL AXIS1(2.0,0.8,2HPC,2,10.0,90.0,PC(K+1),PC(K+2),YMARK)
  000250             CALL SYMBOL(4.0,1.2,0.2,SAMPLE,0.0,20)
  000254             CALL PLOT(2.0,0.8,-3)
  000257             CALL LINE(DELTAT,PC,K,1,-1,3)
  000263             CALL PLOT(6.5,-1.5,-3)
  000266             GO TO 30
  000267         990 IF (NPLOT) 688,688,690
  000271         690 CALL ENDPLT
  000272         688 CALL EXIT
  000273             END
```

Figure F-3. Computer program for theoretical prediction of compressive behavior.



```
SAMPLE B-1S

A/T =  0.570E+01
B/A =  0.100E+01
SHAPE FACTOR =  0.142E+01

     PC             DELTAT          SIGMAC          STRAIN
   0.300E+03      0.120E-01      0.329E+02      0.227E-01
   0.600E+03      0.226E-01      0.658E+02      0.426E-01
   0.900E+03      0.320E-01      0.987E+02      0.604E-01
   0.120E+04      0.406E-01      0.132E+03      0.765E-01
   0.150E+04      0.483E-01      0.164E+03      0.912E-01
   0.180E+04      0.555E-01      0.197E+03      0.105E+00
   0.210E+04      0.621E-01      0.230E+03      0.117E+00
   0.240E+04      0.683E-01      0.263E+03      0.129E+00
   0.270E+04      0.740E-01      0.296E+03      0.140E+00
   0.300E+04      0.795E-01      0.329E+03      0.150E+00
   0.330E+04      0.846E-01      0.362E+03      0.160E+00
   0.360E+04      0.894E-01      0.395E+03      0.169E+00
   0.390E+04      0.940E-01      0.428E+03      0.177E+00
   0.420E+04      0.984E-01      0.461E+03      0.186E+00
   0.450E+04      0.103E+00      0.493E+03      0.194E+00
   0.480E+04      0.107E+00      0.526E+03      0.201E+00
```

Figure F-4 Typical program output.

APPENDIX G

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