ANALYSIS OF MODIFIED BITUMEN ROOFING MATERIALS USING THE STIFFNESS MODULUS

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The introduction of new construction methods and materials to the building industry has changed the needs of roofing design and construction. This combination produces a number of buildings with poor roofing construction with untried materials, and has led to many failures. Consequently, there is a need for analysis methods to evaluate and compare the anticipated performance of materials, and for an engineering design methodology to replace the present design methods that rely primarily on what worked last year.

This paper describes a research project conducted at the University of California (UC) at Berkeley and cosponsored by the UC Berkeley Department of Civil Engineering and the Naval Civil Engineering Laboratory in Port Hueneme, California. The goal of this project is to develop the stiffness modulus analysis methodology for use in an engineering design of modified bituminous roofing systems. The stiffness modulus analysis methodology can be used in conjunction with other methods like strain energy or, with further development, in lieu of some of these methods. Some potential uses include: As a design aid in the engineering design of roofing systems and flashings; as a means of evaluating the mechanical properties of any bituminous material for comparison with those specified; and as a research and analysis tool to help determine the reasons for failures and to track the degradation of mechanical properties during weathering.

Materials have differing capabilities to withstand loads and to deflect to accommodate movement. Bituminous materials are considered to be viscoelastic. That is, they have a complex reaction to load not explainable by "elastic" analysis, but explainable by other methodology. The important factor of the analysis for this study is that the relationship between load and deflection varies with temperature and with rate of loading.

KEYWORDS

Asphalt, construction, engineering design, material testing, mechanical behavior, modified bitumen, performance specification, roofing.

INTRODUCTION

The introduction of new construction methods and materials to the building industry has changed the needs for roofing design and construction. Lighter, more flexible buildings induce more movement in the roofing membrane than did their ancestors. In addition, the removal of several proven materials from the market has necessitated using unproven materials (those with no history of satisfactory performance) in their place. Further, the cost control of many builders and building owners has forced the roofing materials and construction industry into a competitive climate where quality is sometimes sacrificed in order to "get the job." This combination produces a number of buildings with poor roofing construction due to unproven materials, and has led to many failures. Consequently, there is a need for analysis methods to evaluate and compare the anticipated performance of materials and for an engineering design methodology to replace the present design methods that rely primarily on what worked last year. The European standards use performance tests that simulate known failure conditions. One method presently used to analyze modified bituminous roofing materials in the United States is the strain energy analysis of tensile test. While this has a definite advantage over tensile data alone, it also has some difficulties. This paper develops the stiffness modulus for analysis and as a design tool for bituminous roofing systems. The stiffness modulus analysis methodology can be used in conjunction with other methods like strain energy, and with the performance tests developed primarily in Europe or, with further development, in lieu of some of these methods. Some potential uses include:

- As a means of evaluating the mechanical properties of a bituminous material for comparison with those specified.
- As a design aid in the engineering design of roofing systems and flashings.
- As a research and analysis tool to help determine the reasons for failures and to track the degradation of mechanical properties during weathering.

This paper describes a research project conducted at the University of California (UC) at Berkeley and cosponsored by the Naval Civil Engineering Laboratory in Port Hueneme, California and UC Berkeley, Department of Civil Engineering. The project is designed to develop the stiffness modulus analysis methodology, commonly used in asphalt pavement design, for use as a tool in design and construction of roofing systems. The method should be useful in the evaluation of bituminous systems and may also be useful for evaluation of plastic and rubber-based systems.

BACKGROUND

Several researchers have used the stiffness modulus and related methodology to describe the behavior of roofing asphalts under certain conditions. Among these are Carl G. Cash,[1] Roger L. Bonafont,[2] and Michio Koike et al.[3] The original stiffness modulus work for paving asphalts was done by C. Van der Poel.[4]

MATERIAL BEHAVIOR

Materials have differing capabilities to withstand loads and to deflect to accommodate movement. The normal engineering approach to design is to assume that the material exhibits what is known as elastic behavior. That is, it will stretch when loaded in direct proportion to the load and it will return to its original shape and size when unloaded. This assumption relies on the slope of the stress-strain (adjusted load-deflection) curve being relatively straight in the region of concern. The slope of this line is known as the elastic modulus. It is relatively safe to make this assumption for most engineering materials in most service conditions. However, bituminous roofing materials do not exhibit this behavior and must be analyzed differently.

Bituminous materials are considered to be viscoelastic. That is, they have a complex reaction to load not explainable by elastic analysis, but explainable by other methodology. The important factor of the analysis for this study is that the relationship between load and deflection varies with temperature and with rate of loading. The parallel to the elastic modulus for bituminous materials is known as the stiffness modulus and was developed by Van der Poel (1954). This work shows the modulus varies predictably with temperature and with load rate. Further, it shows these variations are interrelated, allowing prediction of material behavior at temperatures and load rates not tested. The stiffness modulus has been used extensively for design and construction of asphalt pavements.

TEST PROGRAM

The goal of this project is to develop the stiffness modulus analysis methodology for use in the engineering design of modified bituminous roofing systems. In order to do this, it was prudent to use automated test control and data collection software, connected to a personal computer and to the test apparatus. The mechanical apparatus consists of an air cylinder, controlled by a servovalve and powered by laboratory air, and connected to a frame. A load cell and three LVDTs (linear variable displacement transducers) are used to take data. Tests were run at several temperatures and at a variety of loading rates, with both load and deflection control.

A four inch diameter air cylinder was fabricated to apply the load to the sample at the rate controlled by the servovalve and computer. The load cell is connected to the shaft of the air cylinder and the sample is attached to the load cell. Two LVDTs are attached to the sample at a three inch gage length. A third LVDT is attached to the shaft of the air cylinder and is used to control deflection. The sample is attached by mechanical clamps, each secured by a wire to avoid eccentric loading. One end is attached to the load cell, while the other end is secured to the frame. The cylinder is also secured to the frame. The sample and part of the apparatus, including the load cell is inside a Missimer's chamber to provide temperature control for testing.

Tests were run at −18°, 0°, 25°, 50° and 70°C (0°, 32°, 77°, 122° and 158°F), respectively, and at varying load rates as discussed below. Load application is controlled by both load rate and deflection rate in order to compare the results.

Dynamic loading is on a sine wave of given amplitude and frequency. This program used an amplitude of 20 psi for load control testing at most temperatures (50°C and 70°C tests were done at lower amplitude to avoid sample failure). An amplitude for deflection control testing was chosen to achieve between 15 and 25 psi load amplitude, when possible. Frequencies used for both load and deflection control testing are 0.01, 0.1 and 1 cycle per second.

The ramp test is a more general name given to the family of tests that includes the standard tensile test. For purposes of this study, it is essentially the same as ASTM D 2523—78 except that two load rates were used in load control (10 pounds/minute and 100 pounds/minute), and three deflection rates were used in deflection control (0.3, 0.03 and 0.003 in./minute) tests.

The test control software is used for both collection of data and load/deflection control. This software is capable of a large variety of tests using varied control and data collection arrangements.

This test program used the dogbone specimen shape of ASTM D 2523—78. Samples were conditioned at temperature for up to 30 minutes before testing, depending on the temperature differential between ambient and that of the test. It was determined from thermodynamic analysis that this was sufficient time to bring the sample to within 1 C of the Missimer's chamber temperature. Humidity is not considered to be a factor in the performance of the material for test method development purposes and is therefore ignored.

This paper uses the information from samples cut in the cross-machine direction of the felt roll, as this is likely to be the weaker, and therefore controlling, direction. It is possible the reinforcing used produces a material that is equally strong in both directions; however, it is not the purpose of this study to determine whether or not this is the case. An ARMA (Asphalt Roofing Manufacturers Association) study[5] shows that the dogbone sample is preferred to rectangular shapes.

TEST RESULTS

Figure 1 shows the load curve for a typical dynamic modulus test. This particular test is at −18°C (0°F) and at 0.1 cycle/second. Figure 2 shows the average of the two LVDTs used to measure deflection for the same test. Figure 3 shows the stress-strain curve for this test. The strain values are adjusted so the strain at the beginning of the test is zero, even though a load is applied at that time. The slope of the stress-strain curve is relatively constant and is called the stiffness modulus or complex modulus, depending on the method of analysis used.

Figure 4 shows the stress-strain curve from the ramp (tensile) test at −18°C (0°F) and 10 lb./minute loading rate. The two additional lines in the curve are the 0.02 percent and 0.2 percent strain offset lines. Note the 0.2 percent strain offset line does not intersect the stress-strain curve in this test. This is because the sample broke at the point of maximum load, exhibiting brittle behavior.

The following formula was used to calculate the stiffness modulus from the dynamic modulus tests. Other properties of the material were also calculated to determine the statistical reliability of the data.

$$\text{Stiffness Modulus} = \frac{\Sigma(\epsilon i \cdot \sigma i) - \Sigma \epsilon i \cdot \Sigma \sigma i/n}{\Sigma(\epsilon i)^2 - (\Sigma \epsilon i)^2/n}$$

where ϵi = strain at point i
σi = stress at point i
n = number of sample points/cycle

Table 1 is the analysis of the test used as an example in Figures 1 through 3.

The stiffness modulus for the ramp tests is calculated from visual observation of the stress-strain curve. The "straight" portion of the curve is taken and the high and low points of this portion used to determine the slope of the curve. This slope is the stiffness modulus.

The software used for this study has a report feature that automatically analyzes raw data from the dynamic test and gives information as in Table 2. The complex modulus of this report is comparable to the stiffness modulus of the other analysis method, while the storage modulus represents the recoverable portion of the complex modulus and the loss modulus gives the unrecoverable portion. These numbers do not add up, as the relationship between moduli is not linear. This software is commercially available by contacting Digital Control Systems of Berkeley, California.

Appendices 1 and 2 summarize the data acquired from this test series for the ramp and dynamic tests, respectively. All numbers are rounded to three significant figures and the dynamic test results are averages over several cycles. Data for tests on one sample are not considered in this analysis as they show extraordinarily high modulus and low stress and elongation. It is assumed that this sample incorporates a reinforcing splice or other abnormality not representative of the membrane material in general.

The dynamic modulus allows generation of a curve for the modulus at each temperature tested. The curve of this study's actual test data at −18°C (0°F) is shown in Figure 5. Shifting the frequency of curves derived from testing at several temperatures allows generation of a curve for the modulus at a given temperature. This curve allows estimation of the behavior of the material at that temperature for load rates not tested. The curve so generated for −18°C (0°F) is shown in Figure 6. Shifting this curve by the calculated adjustment factor allows prediction of the modulus at other temperatures. Computation of this adjustment factor is critical to the success of this method. Ideally, there should be an overlap of moduli for each adjacent section of the curve. In the data for this study, no such overlap exists, indicating that additional tests at intermediate temperatures or greater and lesser frequencies are desirable. The authors used mathematical curve fitting and some approximations to generate the temperature shift factors used herein. They are probably close to the actual factors and are used as an example of the methodology, not as a definitive description of the behavior of this material. The curve of the adjustment factors for the material tested is shown in Figure 7.

Some observations made about this material follow:

- Moderate variation in amplitude of dynamic tests produced no significant difference in modulus.
- The material exhibited higher modulus at lower temperatures as expected (Figure 8).
- Samples tested at 50°C and 70°C (122°F and 158°F) are relatively weak.
- The highest deflections before break were at higher temperatures and lower load rates, as anticipated.
- The bitumen cracks before the reinforcing breaks in low temperature tests.
- Load controlled samples break in two at high temperatures.
- Deflection controlled samples remain intact after the reinforcing breaks at high temperatures.
- The material exhibits higher strength and lower elongation at low temperatures.
- Maximum strain and strain energy do not appear to vary predictably with temperature or load rate.
- Strain energy at 0.02 percent offset does not appear to be reproducible (only two ramp tests were repeated, providing limited data, but in neither case are the strain energies at 0.02 percent strain offset close).
- Strain energy at 0.2 percent offset is better, but not good. (Of the two repeated tests, one is deflection controlled and the other load controlled. The strain energy figures for the deflection control test are close, while those for the load control test are significantly different due to the breakage of the sample at or near the 0.02 percent offset point in one test.)
- Maximum load varies predictably with temperature and load rate (Figure 9).

DISCUSSION

The discussion begins with the definition of failure, because there is apparent disagreement between laboratory and field criteria, and because mode of failure in the laboratory varies with test methodology. Therefore, it is essential to establish reasonable failure criteria before comparing test methods and analysis methods. Then, deflection control and load control of dynamic and ramp tests are compared and contrasted. Following this, the relationship between stiffness modulus and strain energy analysis is explored for ramp test results and the difficulty with the failure definition of strain energy analysis is discussed. Next, the discussion touches on mathematical modeling of stresses and strains in roofing systems, to establish the basis for engineering design using the stiffness modulus. The combination of stiffness modulus results with modeling of stresses and strains allows the designer to predict success or failure of a roofing system.

Failure Criteria

"The roofing system has failed when it no longer keeps the interior of the building dry." This definition is about as straightforward as is possible, but has little relationship to the work necessary to correct the problem. In addition, it is difficult to test a material in the laboratory to predict failure according to this criterion. Dr. Dupuis' definitions[6] of degrees of failure in his article in *Professional Roofing* (July 1990) are appropriate for analysis of modified bitumen materials and fit with this work, with minor modifications. His adoption of "failure levels" to describe the degree of severity of the failures is particularly relevant. Translation of this work to laboratory testing is difficult, however. Several methods of defining failure of laboratory samples have been used by the roofing industry. These include tensile strength, tensile tear strength, elongation at break and other mechanical tests as well as the performance oriented tests developed in Europe.

The strain energy analysis method relies heavily on the proper definition of the limit of the usable portion of the stress-strain curve. The popular opinion that all the area under the curve, up to the point of sample breakage, is usable has some difficulties. This study uses both 0.02 percent and 0.2 percent strain offset lines parallel to the "straight" portion of the stress-strain curve (from which the stiffness modulus is calculated) to analyze strain energy. The difficulty with using the entire area under the stress-strain curve to calculate the strain energy is that the material in service will not remain at one temperature and under constant deflection or loading conditions. If, for example, a roof membrane composed of the material in this study is stressed by deck or insulation movement at a relatively high temperature to the point of reinforcing breakage, the bitumen may remain intact and failure according to the strain energy analysis will not have occurred. Should this membrane then be subjected to a cold temperature, the bitumen will become brittle and stresses due to thermal contraction, wind, etc. will concentrate in the area of broken reinforcing. The bitumen in this area will undoubtedly break, if sufficiently brittle, because the broken reinforcing can not distribute the stresses and strains through this area. Analysis of the strain energy at either temperature relevant to this example would not have predicted this failure. Therefore, it is necessary to consider the failure of the reinforcing as sufficient for failure of the membrane. Additionally, cracking of the bitumen at low temperature may let water into the building, even though the material may be capable of absorbing higher loads or more deflection due to the strength and distortion properties of the reinforcing. In either example, there would be a distinct change in the slope of the stress-strain curve when failure occurs, indicating that the material has undergone permanent, irreversible distortion. The authors suggest the limit of usable strain energy is readily defined by using the stiffness modulus in conjunction with a strain offset to establish a line, as shown in Figure 4.

It is entirely possible that a given material will be capable of excellent service, even after some significant amount of irreversible distortion. In fact, the roofing industry relies upon this fact in order to form flashings of uncured neoprene and other materials, including some modified bitumen sheets. However, since all laboratory analysis and tests are inherently imperfect in describing in-service conditions, the industry must establish some working criteria for laboratory testing and analysis for specifying and comparing materials and systems. The authors also suggest the strain offset line at the slope of the stiffness modulus is worthy of consideration for determining the upper limit of the usable portion of the stress-strain curve in calculation of the strain energy. Reproducibility of the strain energy using this methodology and definition is open to question, based on the difficulties encountered in this study; however, this problem appears to be present regardless of the method used to determine the appropriate upper limit of the usable strain energy. Additional testing should be undertaken to clarify this concern and to discover the proper offset figure for this material. It is probable that this offset figure will vary with temperature and load rate, as well as with the material being tested.

Deflection and Load Control of Testing Contrasted

Deflection and load control of dynamic testing, using the stiffness modulus analysis method, provide results that are sufficiently similar to make it difficult to choose one method over the other. One advantage of load control testing is that it eliminates any distortion of data due to slippage of the sample in the grips, while deflection control is subject to this distortion. Further, load control testing does not require as much adjustment of amplitude for testing with this material as does deflection control. Only at 50°C and 70°C (122°F and 158°F) was it necessary to reduce the load amplitude to avoid breaking the samples in the dynamic tests, while it was necessary to change the deflection amplitude often to avoid premature sample breakage. Either control method is capable of generating meaningful data for ultimate strength and elongation of the material in ramp testing, and a correlation between the test results appears to be possible. Either type of testing can be used to determine the load carrying capacity of the material. The advantage of load control is essentially in the ease of testing.

Mathematical Modeling of Stresses and Strains Induced Upon the Roofing System

Use of the material must consider the loads and deflections anticipated under service conditions. This requires an analysis of the structural support system, particularly how this system will move during service. Koike[7,8] and the researchers at CSNE CSTB UTI[9] have pioneered research in this area. It is also necessary to consider the forces due to wind on the attached membrane, as was done at the Norwegian Building Research Institute.[10] Use of these and similar methods of modeling the stresses and strains induced in the roofing system are necessary for an engineering design of roofing systems. Combined with the stiffness modulus, the designer can then determine the number of layers of the roofing material required to withstand the forces induced on the membrane, or can choose a material with the required strength or deflection capability to withstand that movement.

If the strength of the material at low temperatures is sufficient to overcome the anticipated load, the material should serve satisfactorily. Roofing systems are seldom designed for strength, but are usually designed to accommodate deflections. Therefore, it would require a change from normal design practice to begin designing based on the strength of the material.

Anticipated Uses of Stiffness Modulus as a Design Aid

Analysis of the loads on the roofing membrane that lead to failure should include such known failure scenarios as impact puncture (dropped tools), static puncture (equipment set on the roof), and thermal expansion and contraction of metal flashings adhered to the membrane. Designers can use the load and time criteria derived from this analysis to determine the stiffness required to resist it. Then, this stiffness requirement can be compared to the modulus of the materials to be used at the temperature range anticipated for the loading conditions to determine the adequacy of the material for this use, or to determine the number of layers required to resist the load.

Research Needs

Other areas where the stiffness modulus will prove useful are in the analysis of weathering effects, the effect of repeated loading (fatigue), and in additional examples of known failure mode analysis. Application of the stiffness modulus methodology to study the change in behavior of roofing materials during aging should aid in prediction of the effect of aging on the durability of the roofing system. The materials should become more stiff during aging, therefore the stiffness modulus should increase. Plotting the increase in modulus versus age should yield useful information about the anticipated durability of the roofing system.

Flashings account for the vast majority of roofing system failures, therefore, they should be the subject of most roofing research. Improvements in flashing design and construction will be possible using the stiffness modulus analysis. This approach allows the researcher to model the stresses and strains on the material, and to compare these stresses and strains with the material behavior characteristics. In this way the failure mode can be predicted.

CONCLUSIONS AND RECOMMENDATIONS

- Behavior of modified bituminous roofing materials is predictable from a series of tests and the stiffness modulus analysis methodology.
- The stiffness modulus analysis can aid in selection of the proper upper limit of the usable strain energy.
- Engineering design of roofing systems is possible by combining the stiffness modulus analysis of the material with modeling of the stresses and strains imposed on the roofing system by building movement due to wind, seismic, thermal contraction and other loads.
- The stiffness modulus analysis can help to explain failures, so that the design is not repeated.
- Recommended uses of stiffness modulus analysis method:
  - Analysis of failure modes.
  - Design of improved membrane and flashing systems, using materials more efficiently.
  - Determining the rate and degree of change in the material strength properties during weathering.
- Further research is necessary to develop the stiffness modulus analysis methodology to realize its potential.
- The industry should work toward incorporation of stiffness modulus methodology into performance criteria and design procedures. These criteria should then be incorporated into specifications, ASTM procedures, the NRCA design manual and other industry standard documents. University research could assist in the development of this technology and the government will benefit from the results sufficiently that it should consider major sponsorship of this development.

ACKNOWLEDGMENT

Lewis Painter provided assistance with statistical analysis. Ed Nicks, George Thomas, and Todd Merport of the University of California assisted in the fabrication and assembly of the test apparatus. Matt McCune assisted with the thermodynamic analysis. Jorge Sousa of the University of California and Digital Control Systems assisted with equipment acquisition and set-up and is coauthor of the data collection and test control software. Several manufacturers of materials provided materials for testing.

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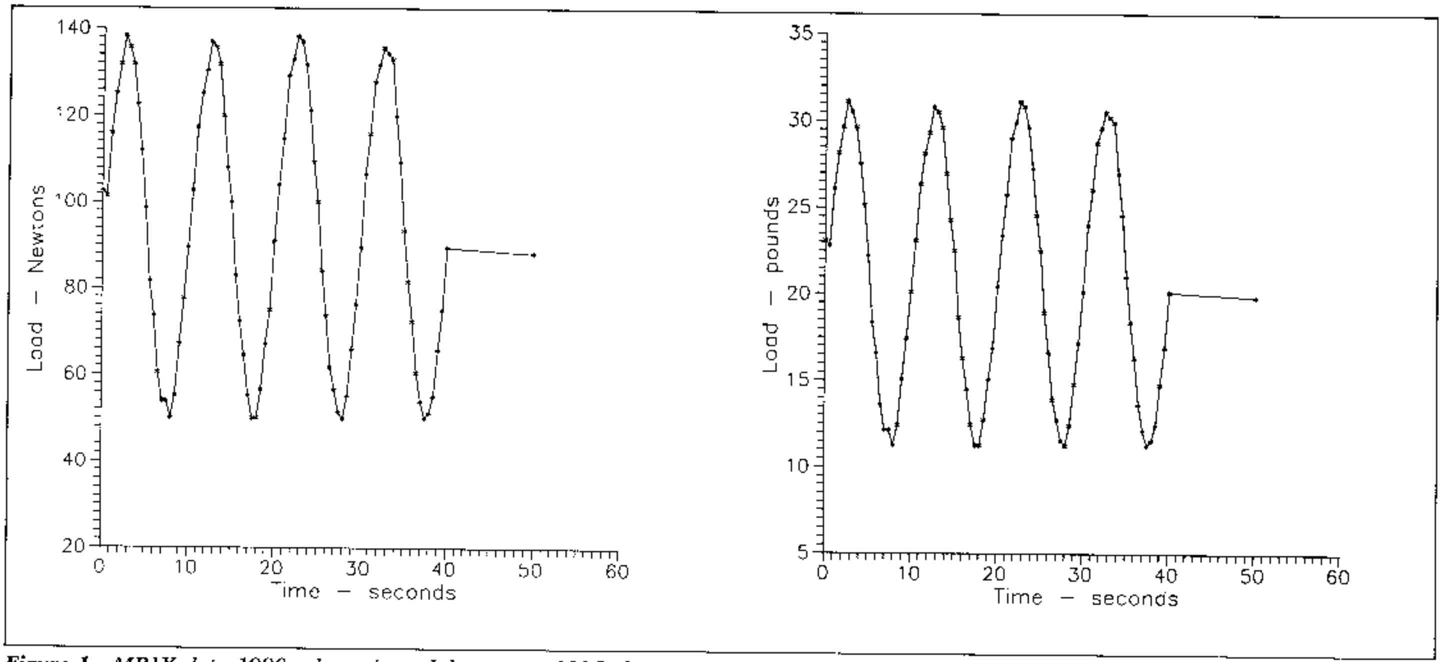

Figure 1 *MB1X data 1990—dynamic modulus test, −18°C, 0.1 cycle/second.*

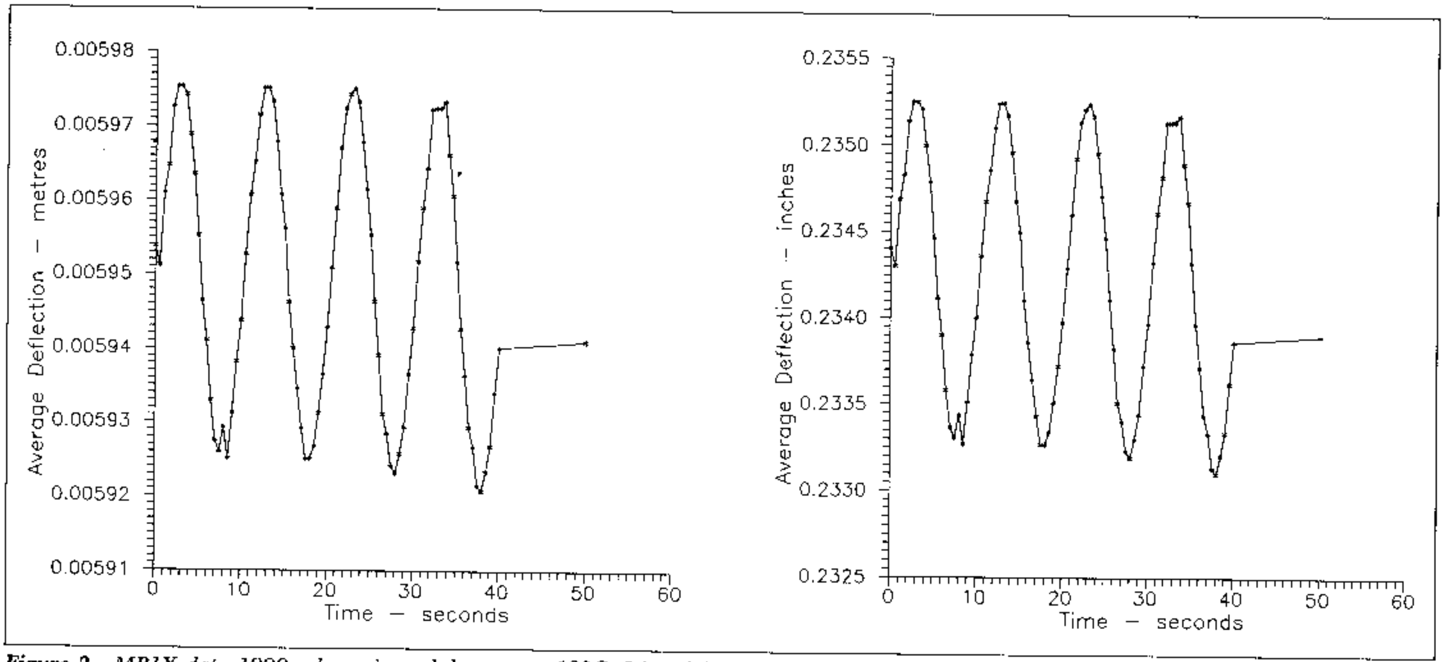

Figure 2 *MB1X data 1990—dynamic modulus test, −18°C, 0.1 cycle/second.*

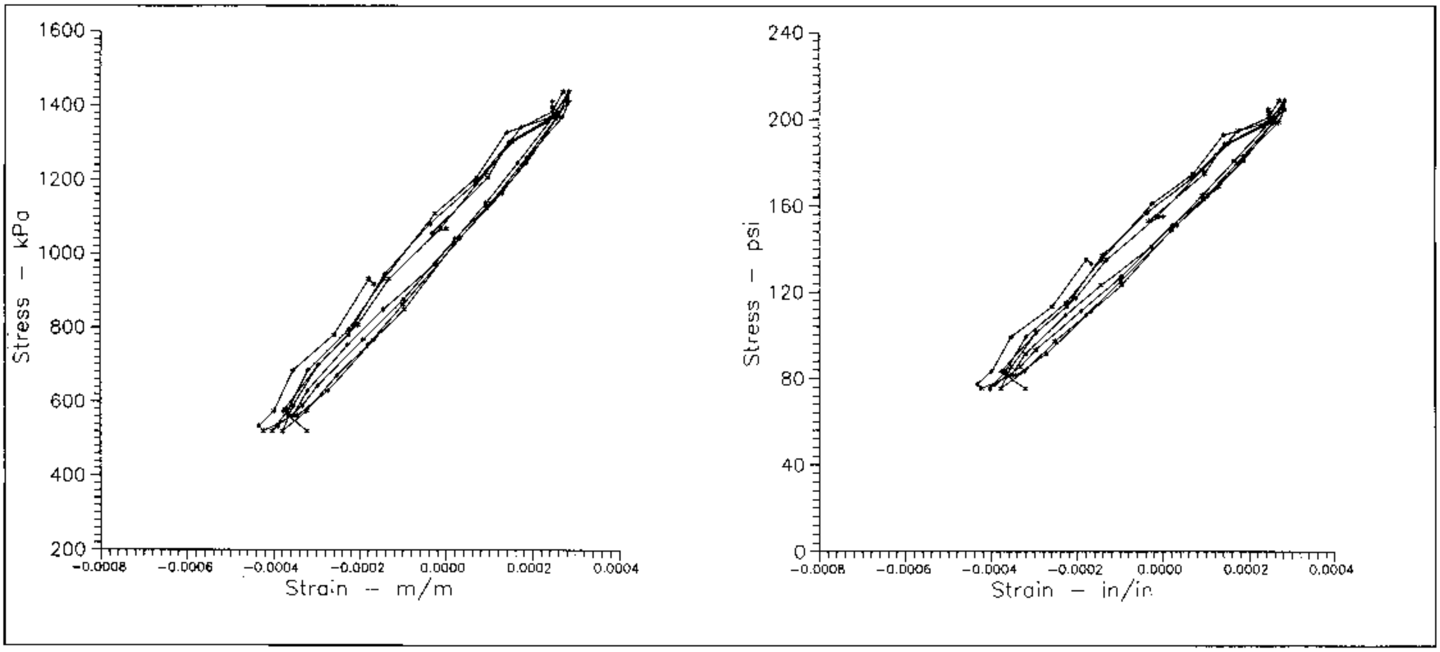

Figure 3 MB1X data 1990—dynamic modulus test, −18°C, 0.1 cycles/second.

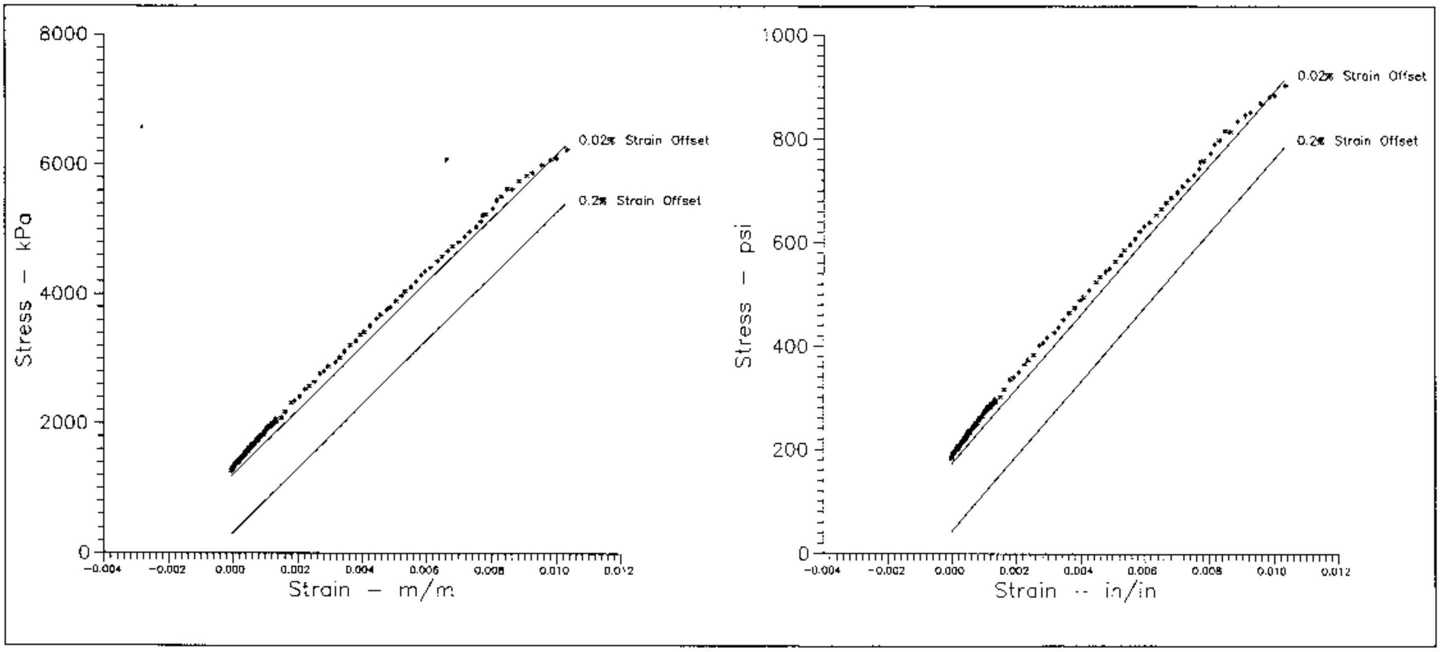

Figure 4 MB1X data 1990—ramp test, −18°C, 10 lb/minute.

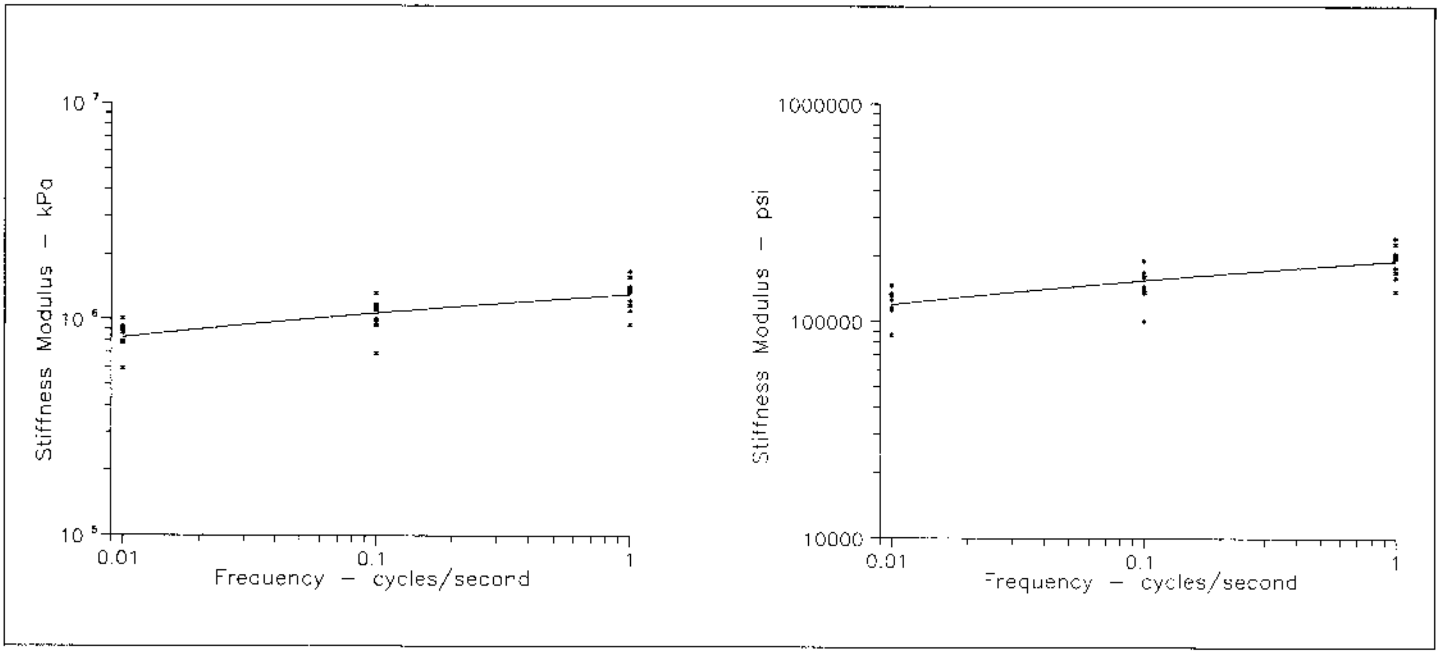

Figure 5 MB1X data 1990, –18°C.

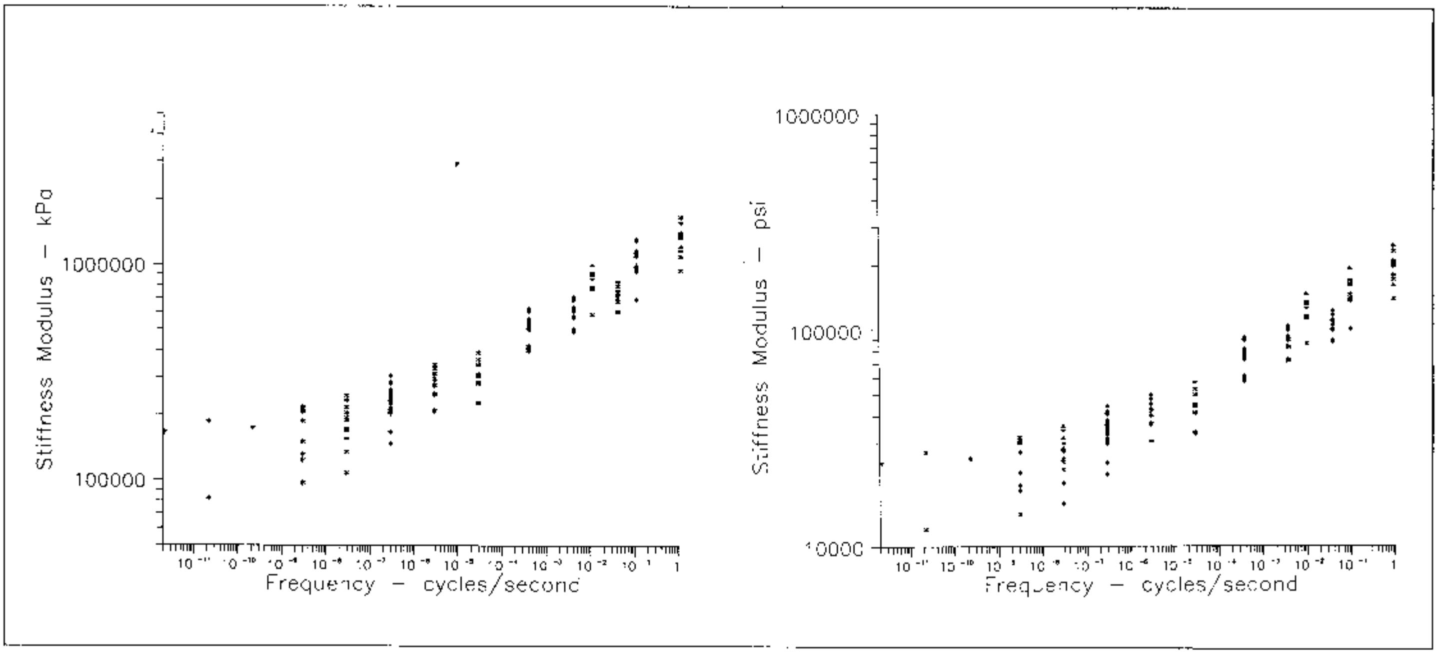

Figure 6 MB1X data 1990—data shifted to form a curve at –18°C.

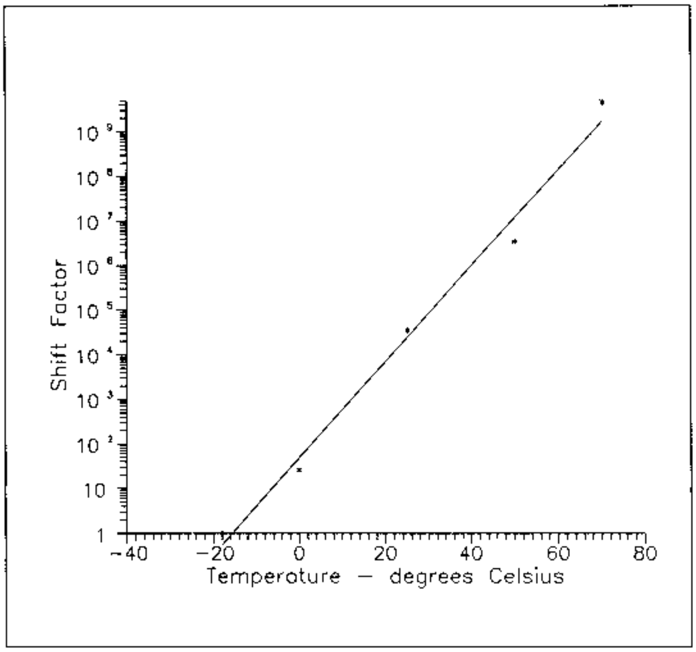

Figure 7 *MB1X data 1990—temperature shift factor.*

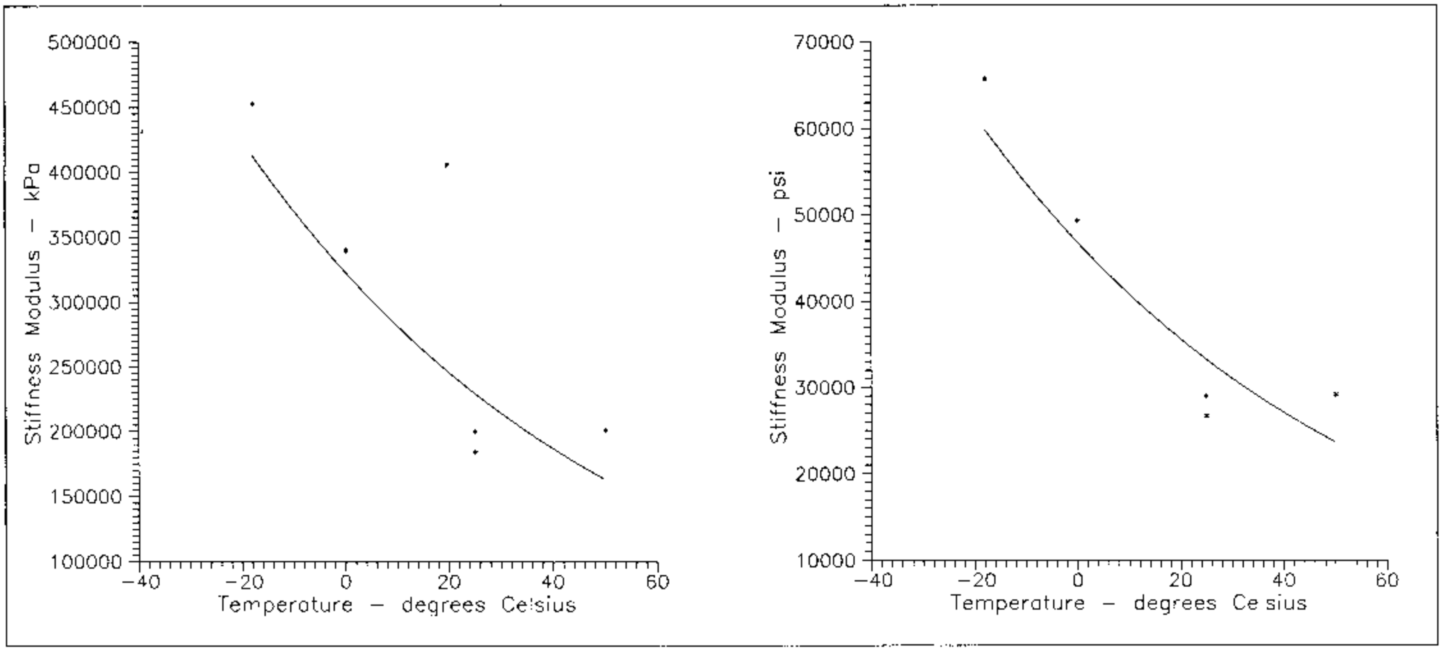

Figure 8 *MB1X data 1990—0.003 in/minute deflection control.*

MBIX data 1990—0.000076 m/minute deflection control.

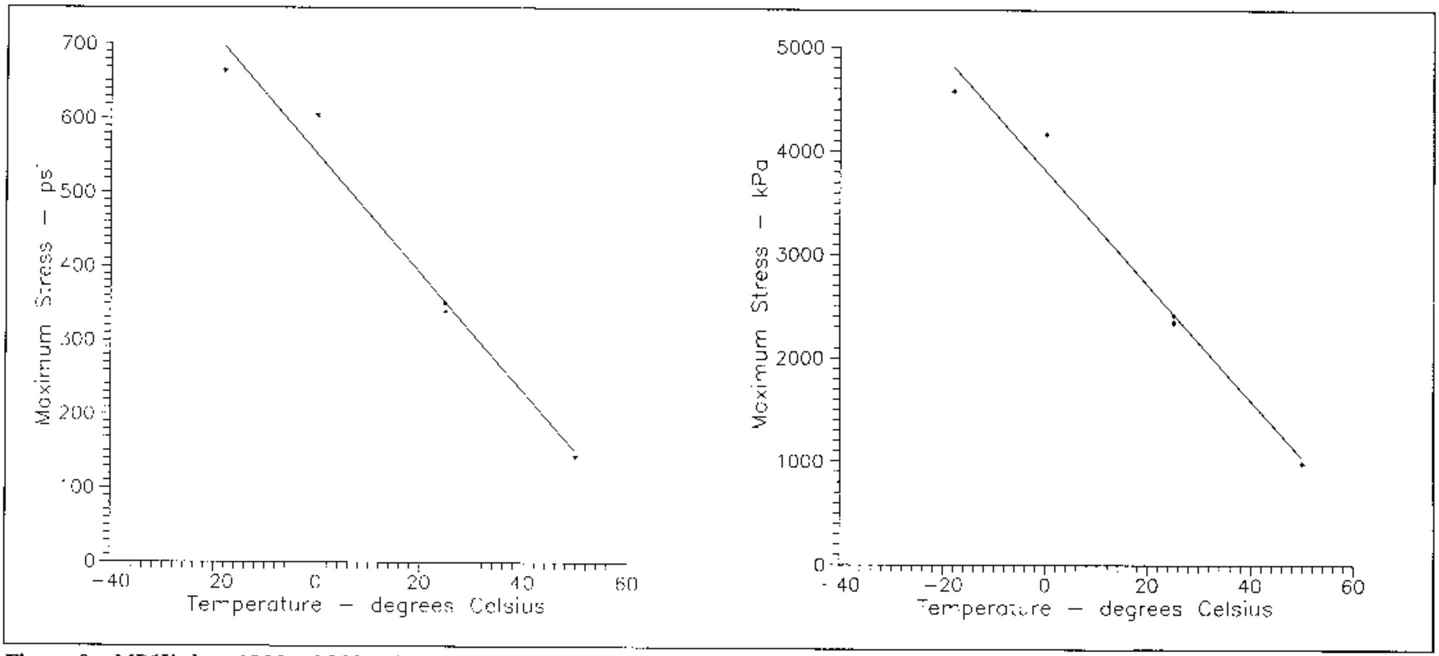

Figure 9 *MB1X data 1990—0.003 in/minute deflection control.*

MBIX data 1990—0.000076 m/minute deflection control.

SI Units
Test # MB1X22BB.WKS

	Cycle 0	Cycle 1	Cycle 2	Cycle 3
Modulus	1341673	1337143	1320070	1279294
sA² strain	5.74E-08	5.67E-08	6.06E-08	6.39E-08
sA² stress	105554	103261	107288	106781
rA²	.98	.98	.98	.98
SSE	43652	35008	31837	42585
MSE	2425	1945	1769	2366

U.S. Customary Units
Test # MB1X22BB.WKS
Temperature = −18°C, Frequency = 0.1 cycle/second

	Cycle 0	Cycle 1	Cycle 2	Cycle 3
Modulus	194594	193936	191460	185546
sA² strain	5.74E-08	5.67E-08	6.06E-08	6.39E-08
sA² stress	2220	2172	2257	2246
rA²	.98	.98	.98	.98
SSE	918	736	670	896
MSE	51.01	40.91	37.21	49.77

Table 1 *Analysis of the load curve for a typical dynamic modulus test.*

SI Units **1 m = 39.3701 in**
file: MB1X22BB.WK1 **1 kPa = .145038 psi**

Time sec	Period none	Ampl. stress kPa	Ampl. strain none	Complex modulus kPa	Storage modulus kPa	Loss modulus kPa	Loss tangent none	Phase angle none	Check sin-integral none	Check cos-integral none	Plastic displ. m
10.5	1	893	6.56E-04	1361030	1350556	168519	.124777	7.11	-5.33E-16	1.29E-09	-3.42E-06
20.5	2	882	6.55E-04	1346730	1335960	169956	.127216	7.25	-7.73E-02	1.29E-09	-3.95E-06
30.5	3	899	6.77E-04	1327114	1317400	160315	.121691	6.94	-7.73E-02	1.29E-09	-4.60E-06
50	4	895	6.93E-04	1291082	1280954	161378	.125982	7.18	-7.73E-02	1.29E-09	-6.39E-06

US Customary Units
file: MB1X22BB.WK1

Time sec	Period none	Ampl. stress psi	Ampl. strain none	Complex modulus psi	Storage modulus psi	Loss modulus psi	Loss tangent none	Phase angle none	Check sin-integral none	Check cos-integral none	Plastic displ. in
10.5	1	130	6.56e-04	197401	195882	24442	.124777	7.11	-5.33E-16	1.29E-09	-1.35E-04
20.5	2	128	6.55E-04	195327	193765	24650	.127216	7.25	-7.73E-02	1.29E-09	-1.56E-04
30.5	3	130	6.77E-04	192482	191073	23252	.121691	6.94	-7.73E-02	1.29E.09	-1.81E-04
50	4	130	6.93E-04	187256	185787	23406	.125982	7.18	-7.73E-02	1.29E-09	-2.52E-04

Table 2 Information from raw data analyzed.

APPENDIX 1

1 N = .224809 lb
1 m = 39.3701 in
1 kPa = .145038 psi

Analysis of Tensile Test Data
Summer 1990
MB1X Specimens

Sample Designation	Temp. Celcius	Load/Defl. Control	Rate N or m /minute	Maximum Strain none	Maximum Stress kPa	Stiffness Modulus kPa	% Strain @ Break	Strain Energy 0.02% Offset kPa	Strain Energy 0.2% Offset kPa
MB1X24BI	-18	Deflection	.000076	.00827	4578	452985	.83%	24.68	25.72
MB1X25BJ	-18	Deflection	.000762	.00367	3661	656380	.37%	13.17	44.20
MB1X26BK	-18	Deflection	.00762	.0122	8549	623285	1.22%	71.02	82.05
MB1X22BG	-18	Load	44.4822	.00922	5881	496422	.92%	37.78	39.37
MB1X23BH	-18	Load	444.822	.00316	3454	688096	.32%	15.65	40.27
MB1X29CI	0	Deflection	.000076	.0101	4164	339911	1.01%	28.27	28.27
MB1X30CJ	0	Deflection	.000762	.00539	2758	368869	.54%	15.17	36.34
MB1X31CK	0	Deflection	.00762	.00689	4082	477806	.69%	23.79	68.81
MB1X27CG	0	Load	44.4822	.00684	3578	417132	.68%	20.13	46.75
MB1X28CH	0	Load	444.822	.00325	2413	510901	.33%	10.00	36.82
MB1X34DI	25	Deflection	.000076	.00867	2413	184090	.87%	16.00	16.00
MB1X06DI	25	Deflection	.000076	.01	2344	199948	1.00%	5.92	16.48
MB1X35DJ	25	Deflection	.000762	.0046	1779	253037	.46%	8.07	21.58
MB1X36DK	25	Deflection	.00762	.0132	3399	215806	1.32%	27.99	27.99
MB1X32DH	25	Load	444.822	.0101	3096	254416	1.01%	22.13	22.13
MB1X05DH	25	Load	444.822	.0143	3316	253727	1.43%	15.10	28.82
MB1X13EI	50	Deflection	.000076	.000954	986	201327	.10%	3.39	7.38
MB1X14EJ	50	Deflection	.000762	.00734	2096	210979	.73%	12.07	16.48
MB1X15EK	50	Deflection	.00762	.00857	2151	182021	.86%	19.03	25.10
MB1X12EG	50	Load	44.4822	.00597	1724	206842	.60%	8.83	8.83
MB1X38EH	50	Load	444.822	.00893	2496	179263	.89%	19.17	19.17
MB1X20FG	70	Load	44.4822	.00653	1413	188227	.65%	.77	5.07

APPENDIX 1

1 N = .224809 lb
1 m = 39.3701 in
1 kPa = .145038 psi

Analysis of Tensile Test Data
Summer 1990
MB1X Specimens

Sample Designation	Temp. Celcius	Load/Defl. Control	Rate lb or in /minute	Maximum Strain none	Maximum Stress psi	Stiffness Modulus psi	% Strain @ Break	Strain Energy 0.02% Offset psi	Strain Energy 0.2% Offset psi
MB1X24BI	-18	Deflection	.003	.00827	664	65700	.83%	3.58	3.73
MB1X25BJ	-18	Deflection	.03	.00367	531	95200	.37%	1.91	6.41
MB1X26BK	-18	Deflection	.3	.0122	1240	90400	1.22%	10.3	11.9
MB1X22BG	-18	Load	10	.00922	853	72000	.92%	5.48	5.71
MB1X23BH	-18	Load	100	.00316	501	99800	.32%	2.27	5.84
MB1X29CI	0	Deflection	.003	.0101	604	49300	1.01%	4.1	4.1
MB1X30CJ	0	Deflection	.03	.00539	400	53500	.54%	2.2	5.27
MB1X31CK	0	Deflection	.3	.00689	592	69300	.69%	3.45	9.98
MB1X27CG	0	Load	10	.00684	519	60500	.68%	2.92	6.78
MB1X28CH	0	Load	100	.00325	350	74100	.33%	1.45	5.34
MB1X34DI	25	Deflection	.003	.00867	350	26700	.87%	2.32	2.32
MB1X06DI	25	Deflection	.003	.01	340	29000	1.00%	.859	2.39
MB1X35DJ	25	Deflection	.03	.0046	258	36700	.46%	1.17	3.13
MB1X36DK	25	Deflection	.3	.0132	493	31300	1.32%	4.06	4.06
MB1X32DH	25	Load	100	.0101	449	36900	1.01%	3.21	3.21
MB1X05DH	25	Load	100	.0143	481	36800	1.43%	2.19	4.18
MB1X13EI	50	Deflection	.003	.000954	143	29200	.10%	.492	1.07
MB1X14EJ	50	Deflection	.03	.00734	304	30600	.73%	1.75	2.39
MB1X15EK	50	Deflection	.3	.00857	312	26400	.86%	2.76	3.64
MB1X12EG	50	Load	10	.00597	250	30000	.60%	1.28	1.28
MB1X38EH	50	Load	100	.00893	362	26000	.89%	2.78	2.78
MB1X20FG	70	Load	10	.00653	205	27300	.65%	.111	.735

APPENDIX 2 1 psi = .145038 kPa

Analysis of MB1X data
Cross-Machine direction

Dynamic Modulus Tests:
Complex Modulus Data from ATS Report analysis
Stiffness Modulus data from spreadsheet analysis
Moduli are averages of available data from one or more cycles.

Filename	Temperature Celcius	Frequency Cycles/sec	Amplitude Stress psi	Amplitude Stress kPa	Complex Modulus psi	Complex Modulus kPa	Stiffness Modulus psi	Stiffness Modulus kPa
MB1X22BD	-18	.01	73	503	87000	599843	86000	592948
MB1X23BA	-18	.01	125	862	123000	848054	125000	861843
MB1X23BD	-18	.01	107	738	114000	786001	113000	779106
MB1X24BA	-18	.01	130	896	150000	1034212	146000	1006633
MB1X24BD	-18	.01	79	545	133000	917001	134000	923896
MB1X25BA	-18	.01	130	896	132000	910106	131000	903212
MB1X25BD	-18	.01	80	552	133000	917001	132000	910106
MB1X26BA	-18	.01	130	896	117000	806685	115000	792896
MB1X26BD	-18	.01	82	565	114000	786001	114000	786001
MB1X22BB	-18	.1	129	889	192000	1323791	191000	1316896
MB1X22BE	-18	.1	90	621	103000	710159	101000	696369
MB1X23BB	-18	.1	130	896	139000	958370	137000	944580
MB1X23BE	-18	.1	126	869	133000	917001	136000	937685
MB1X24BB	-18	.1	128	883	167000	1151422	169000	1165212
MB1X24BE	-18	.1	96	662	168000	1158317	161000	1110054
MB1X25BB	-18	.1	127	876	171000	1179001	168000	1158317
MB1X25BE	-18	.1	102	703	163000	1123843	162000	1116949
MB1X26BB	-18	.1	129	889	140000	965264	140000	965264
MB1X26BE	-18	.1	90	621	145000	999738	145000	999738
MB1X22BC	-18	1	136	938	251000	1730581	244000	1682318
MB1X22BF	-18	1	36	248	141000	972159	138000	951475
MB1X23BC	-18	1	140	965	172000	1185896	170000	1172107
MB1X23BF	-18	1	15	103	171000	1179001	160000	1103159
MB1X24BC	-18	1	134	924	232000	1599581	229000	1578897
MB1X24BF	-18	1	38	262	210000	1447896	204000	1406528
MB1X25BC	-18	1	135	931	214000	1475475	207000	1427212
MB1X25BF	-18	1	39	269	206000	1420317	199000	1372054
MB1X26BC	-18	1	133	917	180000	1241054	178000	1227265
MB1X26BF	-18	1	43	296	208000	1434107	196000	1351370
MB1X03CA	0	.01	132	910	57800	398516	58000	399895
MB1X03CD	0	.01	77	531	61700	425406	61000	420579
MB1X27CA	0	.01	129	889	76000	524001	75000	517106
MB1X27CD	0	.01	118	814	77000	530895	77100	531585
MB1X28CA	0	.01	130	896	81800	563990	81400	561232
MB1X28CD	0	.01	108	745	76800	529516	74500	513658
MB1X29CA	0	.01	129	889	78900	543995	78600	541927
MB1X29CD	0	.01	116	800	73200	504695	72800	501937
MB1X30CA	0	.01	129	889	59800	412306	59500	410237
MB1X30CD	0	.01	102	703	58800	405411	58500	403343
MB1X31CA	0	.01	131	903	89800	619148	89400	616390
MB1X31CD	0	.01	129	889	91800	632938	91500	630869

APPENDIX 2 1 psi = .145038 kPa

Analysis of MB1X data
Cross-Machine direction

Dynamic Modulus Tests:
Complex Modulus Data from ATS Report analysis
Stiffness Modulus data from spreadsheet analysis
Moduli are averages of available data from one or more cycles.

Filename	Temperature Celcius	Frequency Cycles/sec	Amplitude Stress psi	Amplitude Stress kPa	Complex Modulus psi	Complex Modulus kPa	Stiffness Modulus psi	Stiffness Modulus kPa
MB1X03CB	0	.1	136	938	74500	513658	73000	503316
MB1X03CE	0	.1	106	731	72400	499180	72000	496422
MB1X27CB	0	.1	128	883	84200	580538	83700	577090
MB1X27CE	0	.1	135	931	90000	620527	89400	616390
MB1X28CB	0	.1	130	896	91400	630180	90300	622595
MB1X28CE	0	.1	119	820	90500	623974	92500	637764
MB1X29CB	0	.1	128	883	83400	575022	82900	571574
MB1X29CE	0	.1	136	938	83600	576401	83300	574332
MB1X30CB	0	.1	128	883	72100	497111	71600	493664
MB1X30CE	0	.1	122	841	73100	504006	72800	501937
MB1X31CB	0	.1	129	889	100000	689474	100000	689474
MB1X31CE	0	.1	144	993	105000	723948	104000	717053
MB1X03CC	0	1	112	772	87600	603980	88000	606738
MB1X27CC	0	1	137	945	115000	792896	111000	765317
MB1X27CF	0	1	123	848	108000	744632	105000	723948
MB1X28CC	0	1	135	931	101000	696369	98900	681890
MB1X28CF	0	1	121	834	111000	765317	109000	751527
MB1X29CC	0	1	136	938	101000	696369	101000	696369
MB1X29CF	0	1	116	800	102000	703264	101000	696369
MB1X30CC	0	1	134	924	88000	606738	87900	606048
MB1X30CF	0	1	120	827	89700	618459	89000	613632
MB1X31CC	0	1	134	924	117000	806685	117000	806685
MB1X31CF	0	1	125	862	123000	848054	122000	841159
MB1X04DA	25	.01	126	869	40800	281306	40800	281306
MB1X04DD	25	.01	30	207	43800	301990	44400	306127
MB1X05DA	25	.01	127	876	36000	248211	36000	248211
MB1X05DD	25	.01	63	434	37000	255106	37400	257863
MB1X05DL	25	.01	80	552	36500	251658	36200	249590
MB1X32DA	25	.01	131	903	38200	263379	38200	263379
MB1X32DD	25	.01	108	745	37100	255795	37100	255795
MB1X34DA	25	.01	131	903	29600	204084	29600	204084
MB1X34DD	25	.01	100	689	29700	204774	29700	204774
MB1X35DA	25	.01	131	903	41500	286132	41400	285442
MB1X35DD	25	.01	89	614	41800	288200	41600	286821
MB1X36DA	25	.01	130	896	34100	235111	34100	235111
MB1X36DD	25	.01	102	703	33500	230974	33500	230974
MB1X04DB	25	.1	135	931	48000	330948	48000	330948
MB1X04DE	25	.1	50	345	50000	344737	50000	344737
MB1X05DE	25	.1	60	414	42000	289579	42000	289579
MB1X05DM	25	.1	80	552	43000	296474	43000	296474
MB1X32DB	25	.1	130	896	40100	276479	40000	275790

APPENDIX 2 1 psi = .145038 kPa

Analysis of MB1X data
Cross-Machine direction

Dynamic Modulus Tests:
Complex Modulus Data from ATS Report analysis
Stiffness Modulus data from spreadsheet analysis
Moduli are averages of available data from one or more cycles.

Filename	Temperature Celcius	Frequency Cycles/sec	Amplitude Stress psi	Amplitude Stress kPa	Complex Modulus psi	Complex Modulus kPa	Stiffness Modulus psi	Stiffness Modulus kPa
MB1X32DE	25	.1	122	841	40100	276479	40100	276479
MB1X34DB	25	.1	129	889	30300	208911	30300	208911
MB1X34DE	25	.1	111	765	30500	210290	30500	210290
MB1X35DB	25	.1	129	889	45400	313021	45300	312332
MB1X35DE	25	.1	96	662	45300	312332	45200	311642
MB1X36DB	25	.1	130	896	36800	253727	36700	253037
MB1X36DE	25	.1	113	779	36400	250969	36300	250279
MB1X04DC	25	1	135	931	53000	365421	52900	364732
MB1X04DF	25	1	20	138	56700	390932	56900	392311
MB1X05DF	25	1	4	28	45000	310264	45000	310264
MB1X05DN	25	1	6	41	50000	344737	50000	344737
MB1X32DC	25	1	137	945	44000	303369	44300	305437
MB1X32DF	25	1	132	910	44400	306127	44000	303369
MB1X34DC	25	1	130	896	33400	230284	33400	230284
MB1X34DF	25	1	120	827	33000	227527	32900	226837
MB1X35DC	25	1	134	924	50000	344737	49800	343358
MB1X35DF	25	1	110	758	50100	345427	49900	344048
MB1X36DC	25	1	133	917	40900	281995	40800	281306
MB1X36DF	25	1	120	827	41500	286132	41300	284753
MB1X07EA	50	.01	130	896	15600	107558	14100	97216
MB1X08EA	50	.01	130	896	30000	206842	30000	206842
MB1X08ED	50	.01	51	352	30400	209600	30400	209600
MB1X09EA	50	.01	125	862	19100	131690	19100	131690
MB1X09ED	50	.01	105	724	18200	125484	18000	124105
MB1X11EA	50	.01	127	876	27700	190984	27200	187537
MB1X11ED	50	.01	108	745	30300	208911	30300	208911
MB1X12EA	50	.01	128	883	31300	215806	31100	214427
MB1X12ED	50	.01	78	538	30400	209600	30400	209600
MB1X37EA	50	.01	130	896	32100	221321	31800	219253
MB1X38ED	50	.01	123	848	21900	150995	21800	150305
MB1X07EB	50	.1	131	903	28300	195121	28300	195121
MB1X08EB	50	.1	128	883	31600	217874	31600	217874
MB1X08EE	50	.1	62	427	31700	218563	31600	217874
MB1X09EB	50	.1	127	876	19600	135137	19600	135137
MB1X09EE	50	.1	83	572	16000	110316	15700	108247
MB1X10EB	50	.1	121	834	27500	189605	24500	168921
MB1X11EB	50	.1	132	910	30200	208221	29800	205463
MB1X11EE	50	.1	121	834	34000	234421	34000	234421
MB1X12EB	50	.1	131	903	35500	244763	35800	246832
MB1X12EE	50	.1	81	558	29700	204774	29800	205463
MB1X37EB	50	.1	126	869	27500	189605	27400	188916

APPENDIX 2 1 psi = .145038 kPa

Analysis of MB1X data
Cross-Machine direction

Dynamic Modulus Tests:
Complex Modulus Data from ATS Report analysis
Stiffness Modulus data from spreadsheet analysis
Moduli are averages of available data from one or more cycles.

Filename	Temperature Celcius	Frequency Cycles/sec	Amplitude Stress psi	Amplitude Stress kPa	Complex Modulus psi	Complex Modulus kPa	Stiffness Modulus psi	Stiffness Modulus kPa
MB1X37EE	50	.1	62	427	25400	175127	25200	173748
MB1X38EE	50	.1	129	889	22700	156511	22600	155821
MB1X07EC	50	1	130	896	29000	199948	30000	206842
MB1X08EC	50	1	125	862	32900	226837	32900	226837
MB1X08EF	50	1	49	338	34600	238558	34600	238558
MB1X09EC	50	1	132	910	21500	148237	21400	147548
MB1X11EC	50	1	140	965	35700	246142	35700	246142
MB1X11EF	50	1	106	731	35200	242695	34900	240627
MB1X12EC	50	1	137	945	36600	252348	36000	248211
MB1X12EF	50	1	92	634	31700	218563	31100	214427
MB1X37EC	50	1	121	834	31700	218563	31300	215806
MB1X38EF	50	1	152	1048	24200	166853	24200	166853
MB1X39FD	70	.01	73	503	24300	167542	24100	166163
MB1X39FB	70	.1	96	662	13700	94458	12000	82737
MB1X39FE	70	.1	65	448	27500	189605	27100	186848
MB1X39FC	70	1	63	434	25400	175127	25300	174437