LOW TEMPERATURE TENSILE PROPERTIES OF ASPHALTS

A Senior Thesis

By

Scott Moffatt

1996-97 University Undergraduate Research Fellow

Texas A&M University

Group: ENGINEERING

Low Temperature Tensile Properties of Asphalts

Scott G. Moffatt
University Undergraduate Fellow, 1996-1997
Texas A&M University
Department of Chemical Engineering

APPROVED

Fellows Advisor ______________

Honors Director ______________

Table of Contents

List of Figures

List of Tables

Introduction

Objectives

The purpose of this research was to determine what effects composition, temperature, rubber content, and aging time have on the low temperature properties of various asphalts. These properties, failure stress, failure strain, and stiffness, will help in understanding what factors cause premature failure in roadways at low temperatures.

Background

Asphalts are a film that are used to glue the rocks together on roadways. As cars drive over the roads, they cause tensile loads on the asphalt which cause the roads to crack. The maximum tensile stress that a road can withstand is one defining property that can be used to compare the lives of different asphalts. The asphalt mainly cracks under thermal stresses at low in-service temperatures because the asphalt binder behaves in a brittle manner (Instron 1995). It also is under increased stresses because asphalts contract and stretch at low temperatures. Asphalts in roads can be classified as a continuous film, and therefore tested as such.

Repairing cracked roads in the United States costs hundreds of million dollars a year (Bullin 1995). Asphalt is the substance most used as a road surfacing material and a glue that holds the aggregate together. During the life of the asphalt, it undergoes a large amount of oxidation and hardens as a result (Bullin 1995). This leads to the brittle behavior and the cracking of the road. These cracks lead to additional corrosion via water and additional oxidation (Bullin 1995) . The premature failure of roads requires a tremendous amount of the taxpayers money every year. In Texas, for example, the highway system is the number one expenditure of the government and is therefore a very important issue.

Composition of the asphalt and the amount of aging, or percent oxidation, is also very important to the lifetime of roadways. There are several characteristic types of asphalts called the SHRP (Strategic Highway Research Program) Core 8. The composition of asphalt is dependent on the reservoir that the oil was taken from and the processes used to produce the asphalt. The composition of asphalts also varies considerably with crude source, time of year, and refining methods. Several additives to asphalts are being researched in order to improve their composition. These include recycled tire rubber, as mandated by the United States government, and polymer additives (Bullin 1995). The rubber additive is meant to make the asphalt less brittle at low temperatures and therefore less susceptible to cracking. The rubber adds its elastic properties to the rubber which make it able to undergo more strain, or stretching, before it breaks.

The majority of the asphalts used in the direct tension tests were asphalt-rubber blends prepared by Travis C. Billiter. The processes used to prepare these Silverson blends are explained in detail in his dissertation, “Physical Properties of Asphalt-Rubber Binder.”

Materials and Methods

In order to determine the failure stress and strain of various asphalt and asphalt-blend samples an Instron Model BTI-3 Direct Tensile Testing System (DTTS) for Asphalt Binder was used. The Instron machine plots the stress-strain curve for each sample tested. The slope of the chord from the origin to the point of failure is a property called failure stiffness. This is calculated by dividing the failure stress by the failure strain. The stress and strain at failure are determined from data gathered by the DTTS. A simplified stress/strain curve is seen in *Figure 1: Simplified Stress/Strain Curve*.

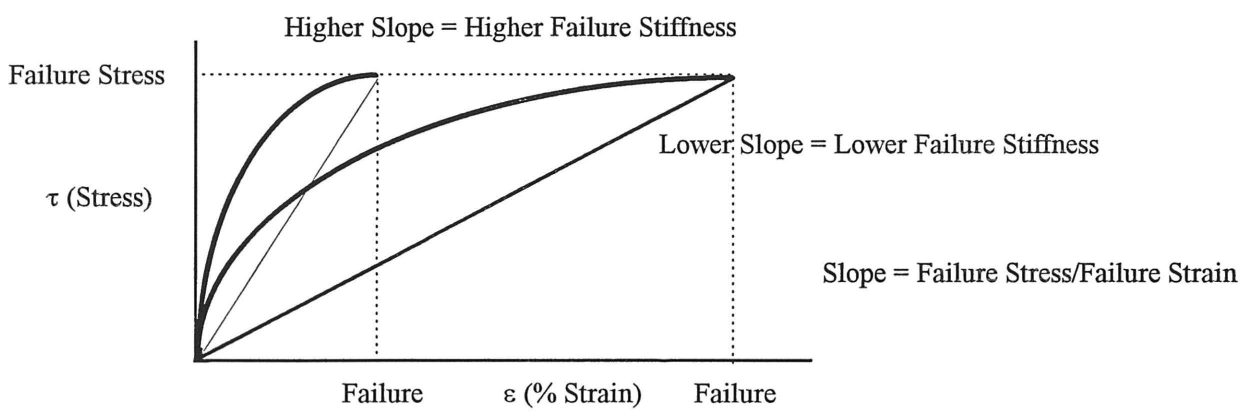


Figure 1: Simplified Stress/Strain Curve

The Instron DTTS has a temperature control bath that can produce temperatures between -40 and +25°C and can maintain the temperature within 0.2 °C. It can deliver up to 500 N (100 lbs) of force with a DC servomotor and a ball screw actuator. It also has a data acquisition control system that has a Windows-based graphical interface and that provides real time plots on a computer display (Instron 1995). The direct tension testing procedure described by SHRP was used in all experimentation. See *Appendix A: Direct Tension*

Testing Procedure, for a detailed description of the procedure used to obtain this data. A dogbone-shaped specimen was tested at a constant rate of elongation at a specified temperature. The stress and strain at failure were calculated using the initial cross-sectional area and the effective gauge length of the specimen, the load at failure, and elongation at failure (Kennedy 1995). This was done automatically by the Instron DTTS.

Failure stress is the maximum tensile stress that the specimen can withstand. The failure strain is the tensile strain corresponding to the failure stress. The stiffness modulus was calculated by dividing the failure stress by the failure strain. The Instron DTTS was operated at a constant strain rate of 0.375%, 0.1 mm, per minute. The data acquisition rate was set up to read one sample set per second so that accurate peak values could be determined.

Testing Core Asphalts

Tests were performed on several SHRP core asphalts including: AAA-1, AAD-1, AAM-1, AAB-1, AAF-1, and AAG-1. Data on the failure properties of these asphalts including failure stress, failure strain, and stiffness modulus are included in *Appendix B: Direct Tension Data* for the asphalts that were tested. Also included with this report in *Appendix D: SHRP Core Stress-Strain Curves* are stress-strain curves of these asphalts that were produced with the direct tension test data.

Testing Rubber Blends

Several asphalt-rubber blends were also tested, and consisted of the main bulk of the experimentation. The so-called "Silverson" blends consist of either Exxon AC-10 or

Fina AC-5 as a base asphalt mixed with rubber under different conditions. The AC-10 designation corresponds to a viscosity at 60°C of about 1000 poise, and the AC-5 corresponds to a viscosity at 60°C of about 500 poise. The Fina AC-5, therefore, is a softer, or less stiff, asphalt.

The standard Silverson blend was cured for 6.5 hours at 500 degrees Fahrenheit, mixed at 4000 revolutions per minute in a Silverson mixer, and contains 10% rubber with a -10 mesh size, designated TG -10 because the rubber was supplied by Tire Gator. These variables were changed to see how each affected the properties of the asphalt. The changed variables were curing at 450 degrees Fahrenheit, mixing at 8000 revolutions per minute, using TG -40 grade rubber, and using 20% rubber content. These standard blends were all aged in a Pressure Aging Vessel (PAV) at 20 atm and 100 degrees Celsius for 20 hours. The base asphalt in each case was also tested without the addition of rubber, or neat. Selective Silverson blends were also tested before being aged in the PAV and are considered unaged samples. Additionally, the two standard Silverson blends were tested after being aged at 140 degrees Fahrenheit and 1 atmosphere for 307 days.

Results and Discussion

Extensive data were obtained that show the dependence of failure properties on rubber content, temperature, aging, and curing conditions. Numerical values for failure stress, strain, and stiffness modulus can be seen in *Appendix B: Direct Tension Data.* Included in *Appendix D: SHRP Core Stress-Strain Curves, Appendix E: Exxon Silverson Stress-Strain Curves* and *Appendix F: Fina AC-5 Silverson Stress-Strain Curves* are plots of stress versus strain for all tests performed. It should be noted that whenever a failure strain is reported to be 3.75%, either graphically or in the data table, this corresponds to the maximum strain that can be read by the DTTS (1 mm) and therefore is not the actual failure point of the asphalt. However, this was assumed to be the failure point when interpolating on generated graphs.

Accuracy of Data

Failure properties are inherently very sensitive to small flaws in materials. Therefore, great care was taken to eliminate all sources of outside flaws from the asphalt specimens in order to isolate the failure due to the structure of the asphalt. These points of error include eliminating air bubbles and trimming errors, and the re-use of asphalt specimens. A detailed description of these problems and their solutions is found in *Appendix C: Error Reduction.* Despite these extensive efforts, there was still significant scatter in the values of the failure stress and strain. However, the stiffness should, and did, remain constant throughout most of the trials. The exceptions were likely caused by improper stirring of the asphalt before pouring and the inherent in-homogeneity of asphalt rubber.

Rubber Composition Dependence

There are several interesting trends associated with varying the rubber content of asphalts. See *Appendix G: Rubber Content Dependence of Failure Properties* for graphical comparisons. In comparing the graphs of Exxon AC-10 with and without rubber, there is a great decrease in the stiffness of the asphalt at -18 degrees Celsius when rubber is added. This is shown in *Figure 2: Rubber Composition Comparison*.

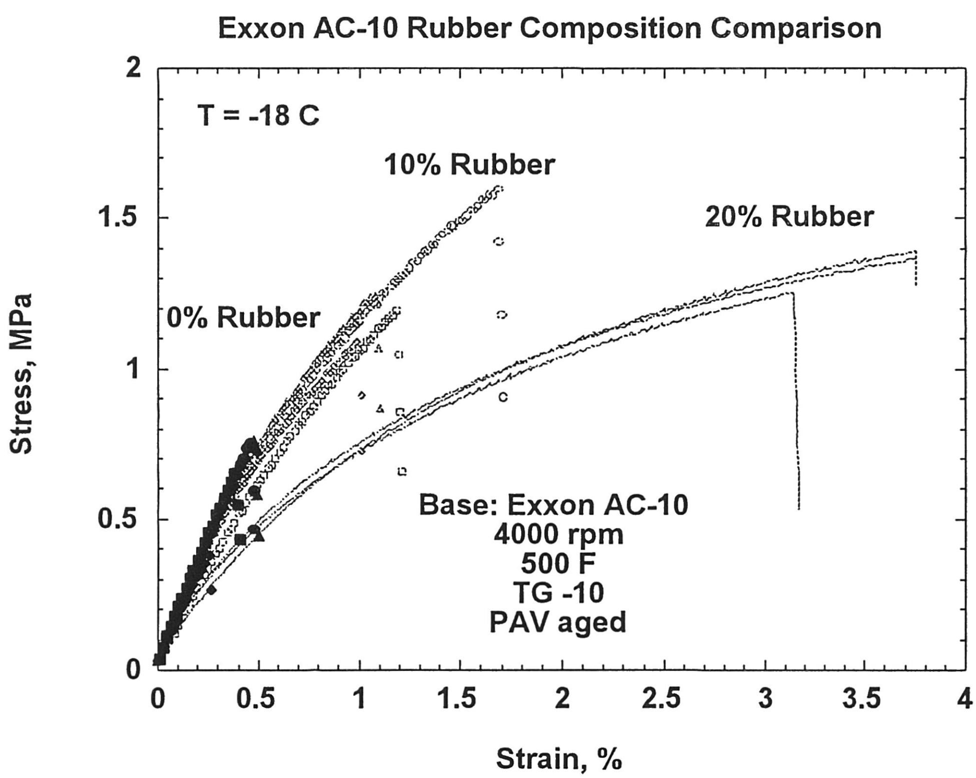


Figure 2: Rubber Composition Comparison

The failure stress of the asphalt also increased slightly with the addition of rubber. Both of these factors combined to give a much higher failure strain at a constant temperature for the asphalt-rubber blends as compared to straight asphalt. This is a desired low temperature property of asphalt, and should increase the SHRP performance grade of this asphalt significantly. Note that three of the trials for Exxon AC-10 with 20% rubber went to the maximum 1 mm elongation ,or 3.75% strain, that the DTTS can read. Therefore the actual failure stress and strain values for 20% rubber content are even higher than shown on the graph.

Temperature Dependence

The failure properties and the stiffness of each asphalt are highly temperature dependent. These relationships can be seen graphically in *Appendix H: Temperature Dependence of Failure Properties*. Most asphalts were tested at both -18°C and -24°C. As seen in *Figure 3: Temperature Dependence*, the stiffness of the asphalt samples increased with decreasing temperature.

The failure stress and failure strain both decreased with a decrease in temperature, some asphalts more than others. The change in failure strain versus the change in degrees Celsius for most of the Silverson blends was on the order of 0.27 mm/°C. Two blends have a much higher temperature dependence, the unaged rubber blends and the 20% rubber blends with bases of both Exxon AC-10 and Fina AC-5. In these blends the slopes are around 1.0 mm/°C. This seems to be mostly due to the much higher failure strain at -18°C.

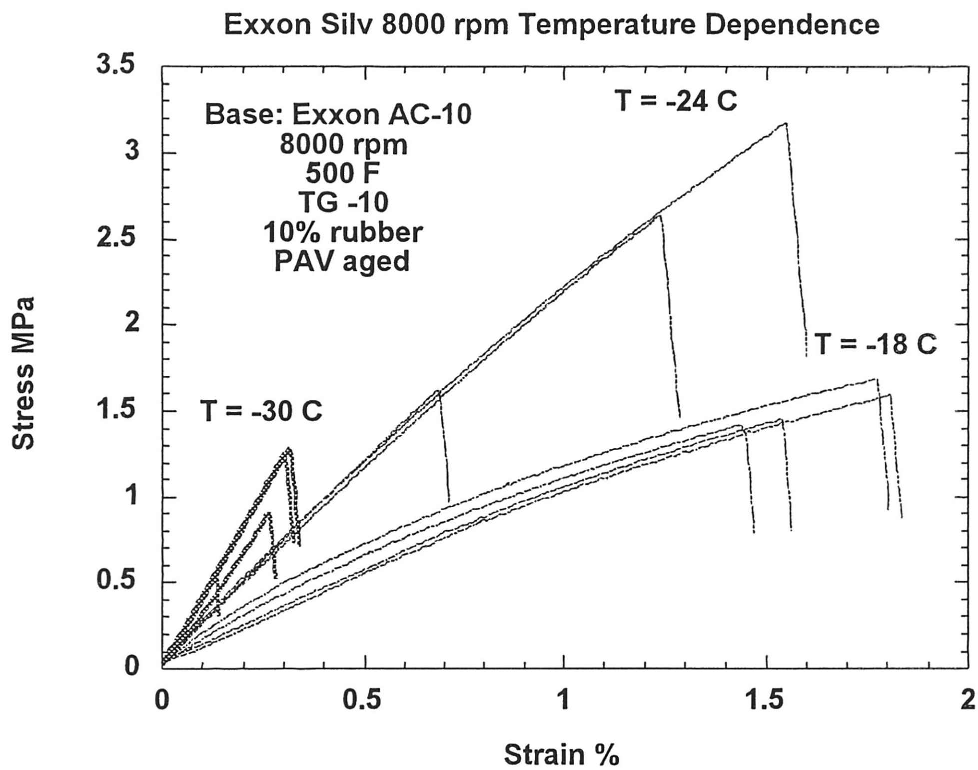


Figure 3: Temperature Dependence

The failure strain is of particular interest at each temperature because of the SHRP performance grading procedures. When using the direct tension test to grade asphalts, the failure strain at a certain temperature must be greater than 1% in order to pass SHRP specifications. The temperatures that each specimen would first pass this specification, or have a 1% failure strain, were interpolated based on the temperature dependence, and can be found in the table below. It should be noted that the SHRP specifications call for the asphalt to be tested at a strain rate of 1mm/min but these tests were run at 0.1mm/min. All of the rubber blends, with the exception of the Exxon AC-10 without rubber, had an extrapolated 1% failure strain at temperatures around -20 °C. The two SHRP Core 8 asphalts had values about five to seven degrees higher. These data show that the addition of rubber is accompanied by a significant decrease in the temperature at 1% failure strain. This decrease is an improvement in the SHRP performance grade for asphalts that contain rubber.

Specimen	Specimen
1. Exxon Standard	8. Fina 8000 rpm
2. Exxon 8000rpm	9. Fina TG -40
3. Exxon TG -40	10. Fina 450 F
4. Exxon 0% rubber	11. Fina 20% rubber
5. Exxon 20% rubber	12. Fina Standard Unaged
6. Exxon Standard Unaged	13. AAD-1
7. Fina Standard	14. AAM-1

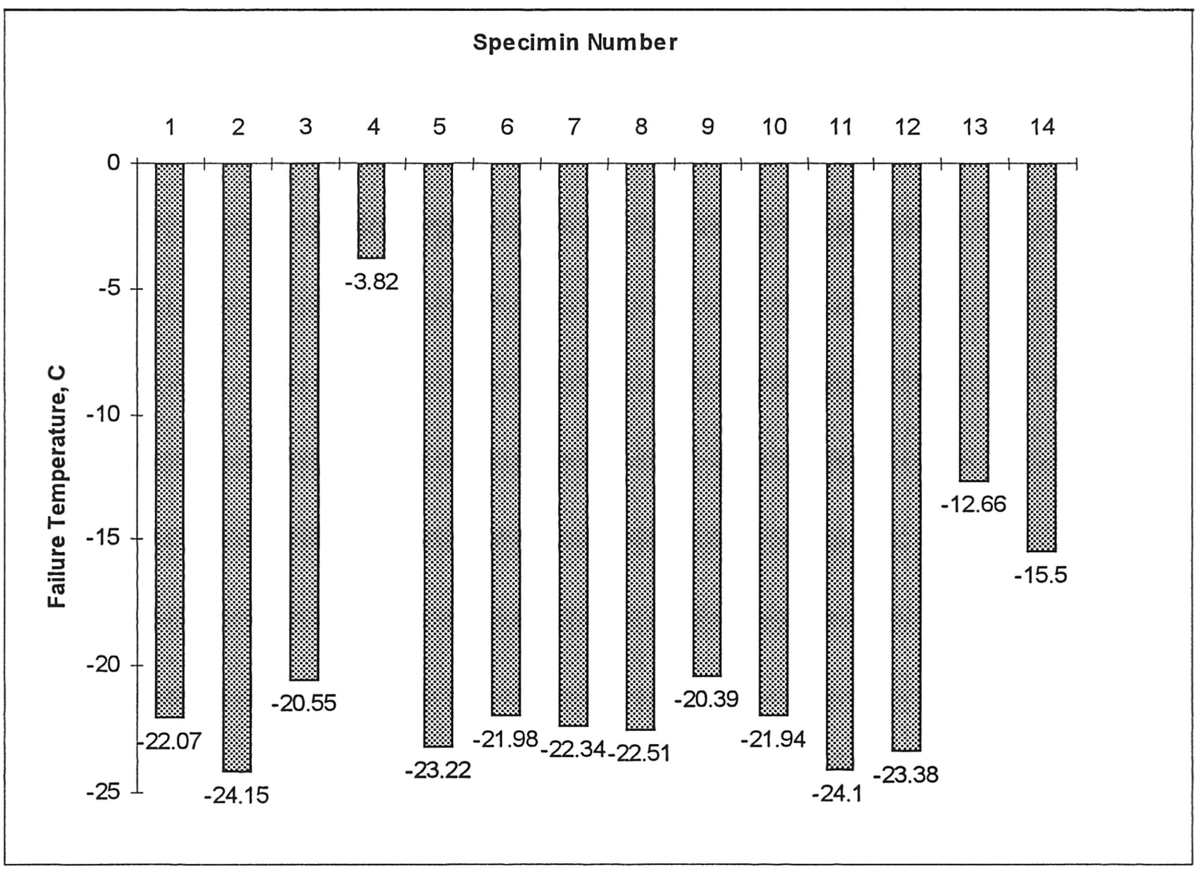


Figure 4: Temperature of 1% Failure Strain

Aging Dependence

The aging level of asphalts can be correlated to carbonyl area, or percent oxidation, in order to be easily comparable. The higher the value for carbonyl area, the more aged a sample is. Values for carbonyl area for each aging procedure are in Table 1. These values were found from the infrared spectrum of each specimen.

Table 1: Carbonyl Area

Specimen	Average Carbonyl Area	Standard Deviation
Exxon Silverson Standard Unaged	0.599746	0.009656
Exxon Silverson Standard PAV Aged	0.945025	0.009429
Exxon Silverson Standard 140F Aged	1.325400	0.010219

The asphalt aged in the PAV was aged for 20 hours at 20 atm and 100 °C, and the asphalt aged in the environmental room was aged for 307 days at 1 atm and 140 °F. Aging plays a significant role in failure of asphalts on roadways. The experimental data show that increased carbonyl area accompanied a similar trend to decreasing the rubber content. The stiffness increased and the failure stress and strain were significantly lowered as seen in *Figure 5: Aging Comparison*. The asphalt aged at 140°F has the greatest carbonyl area and therefore the greatest stiffness and lowest failure strain. The failure stress is slightly higher because of the increased stiffness.

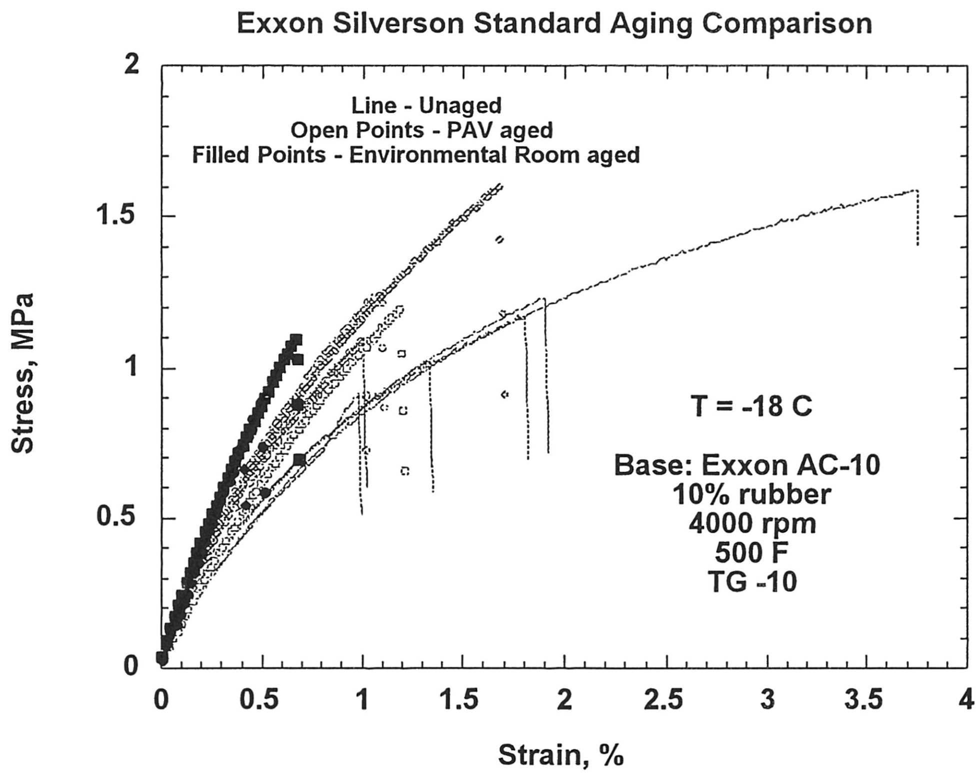


Figure 5: Aging Comparison

Curing Dependence

Another conclusion that can be drawn from these data is that the rubber blends that are the most homogenous improved the low temperature properties the most. The most striking observation was the difference between the relative performance of the 8000 rpm blend at -18 and -24 degrees Celsius. At -18°C the failure properties of the 8000 rpm blend were close to the same as the Silverson standard. However, at -24°C the 8000 rpm blend significantly outperformed all of the other blends. This is likely due to the increased homogeneity achieved by mixing the rubber at 8000 revolutions per minute. This phenomenon is seen in Figure 6. In most cases, the mesh size had little or no effect on the failure strain. When it did, the TG -40 gage (which contains smaller rubber particles) actually gave lower failure strains. The stiffness was essentially unaffected with different gage rubber. This is probably due to the fact that all of the Silverson blends were highly cured and therefore after curing both mesh sizes had about the same homogeneity. The dependence of failure strain on curing temperature is also very small. Curing the rubber at 500°F rather than 450°F gives slightly higher failure strains, possibly because of increased homogeneity achieved at the higher temperature.

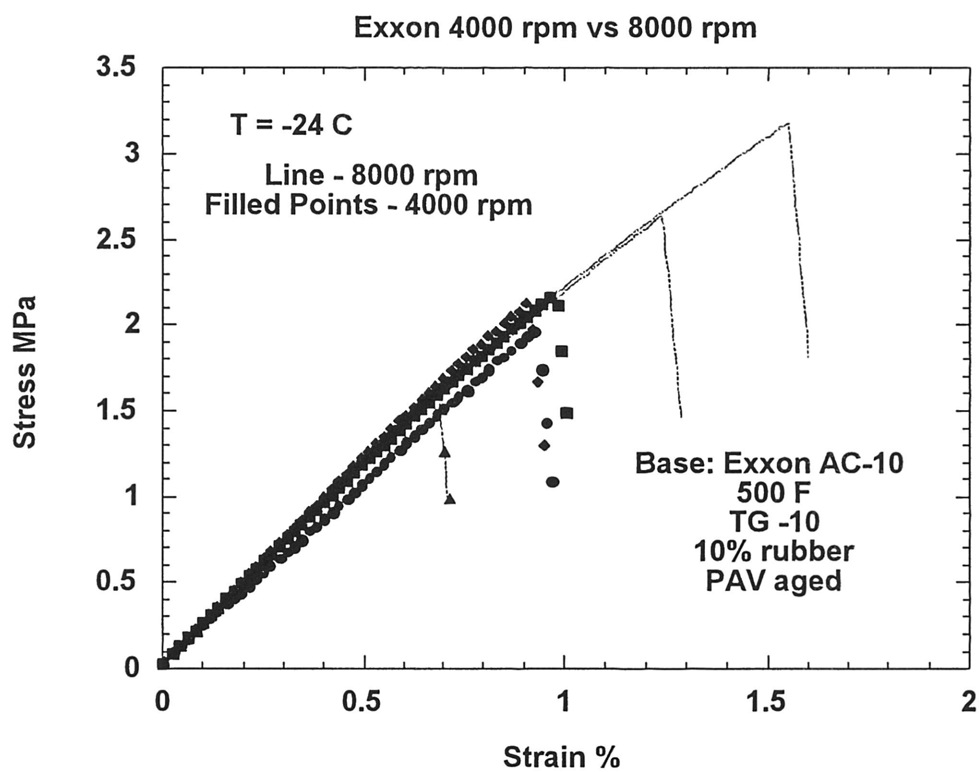


Figure 6. Curing Comparison

Other Comparisons

There are several other interesting features of these data. The failure properties of some of the SHRP Core-8 asphalts were measured. These were not extensively tested and therefore their failure properties can only be compared with one another.

Several of the Silverson blends were also tested on a Bending Beam Rheometer. This test gave values of stiffness for each asphalt while subjected to a constant load for one minute. These can be compared to stiffness values found directly from the direct tension test. These data can be seen in *Appendix B: Direct Tension Data.*

Another relationship that can be observed is the dependence of these failure properties on strain rate. This dependence was not extensively explored, but the data that were gathered suggest that the stiffness increases with increased strain rate. Along with this is a decrease in the failure stress and strain when strain rate is increased. These trends are expected because the properties of visco-elastic materials like asphalts are strain rate dependent. An increased strain rate causes increased resistance by the asphalt, which corresponds to a greater stiffness. This can be seen in Figure 7 below. This figure shows the strain rate dependence of two of the SHRP Core 8 asphalts.

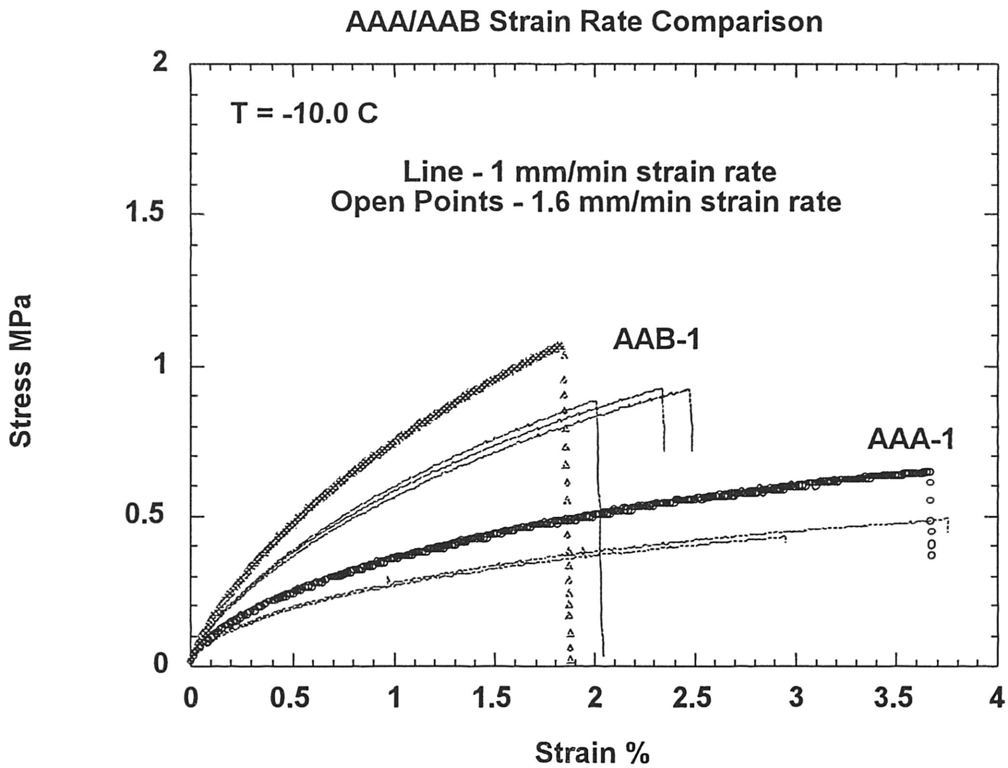


Figure 7. Strain Rate Comparison

One of the most interesting discoveries is a strange phenomenon seen in several of the asphalts. This consisted of several changes in the stiffness of the asphalt as the test proceeded. As seen in *Figure 8: Stiffness Phenomenon*, there are at least three distinct regions of different stiffness. This phenomenon was seen in only four specimens, Fina AC-5 Silverson Standard unaged at -18°C, Exxon AC-10 Silverson 20% rubber at -18°C, Fina AC-5 Silverson 20% rubber at -18°C, and slightly in the Exxon AC-10 Silverson Standard unaged at -18°C. It is likely that this phenomenon will occur in other asphalts at different temperatures, although the cause of this phenomenon is not known. It could possibly be caused by a kind of restructuring of the molecules in these samples, similar to the behavior of some polymers. This only occurred in the Fina AC-5 unaged Silverson standard sample and the two Silverson 20% rubber samples all at -18°C. It is unclear what relationship these samples have to each other and the exact reason that this phenomenon occurs. One suggestion is that each of these samples has a different visco-elastic memory due to the loading history of the asphalt. In order to try to determine if this is the cause, experiments could be performed that repeatedly subject each sample to the same history. This might remove all differences in visco-elastic memory that each sample has.

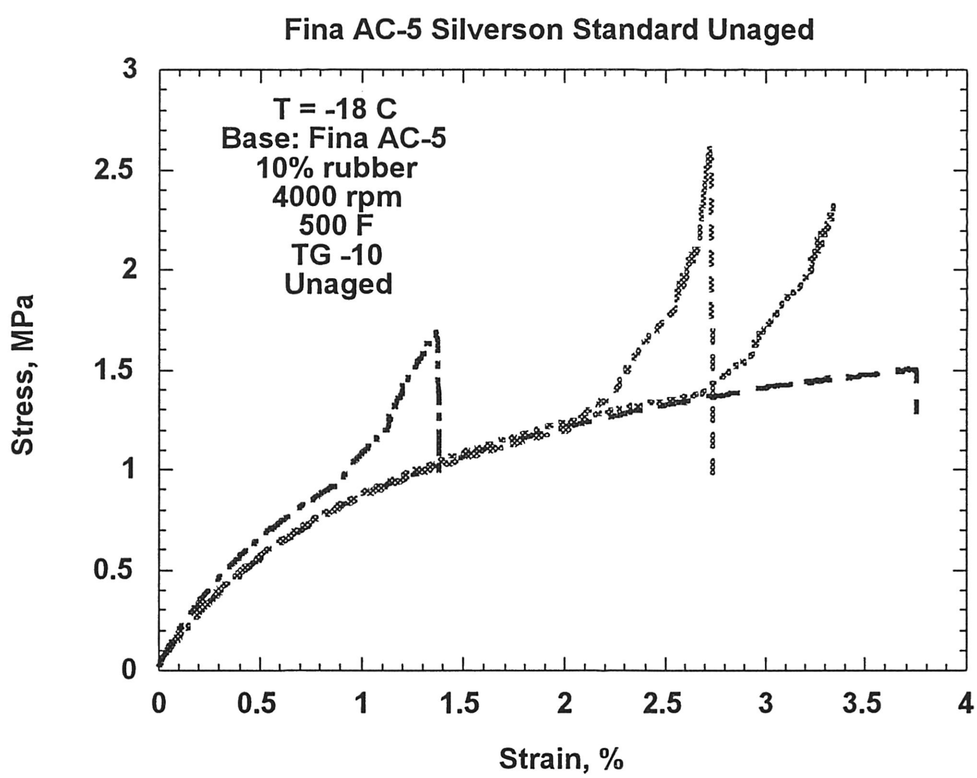


Figure 8: Stiffness Phenomenon

Recommendations and Conclusions

There are several additional experiments that could be done to enhance this research and discover more about the low temperature tensile properties of asphalts.

Experiment 1: Perform direct tension tests on neat asphalts that vary aging times in order to better correlate carbonyl area with failure properties and compare the aging of neat asphalts to the aging of asphalt-rubber blends. Experiments could be done for unaged, PAV aged, Rotating Thin Film Oven (RTFO) aged, and for various exposure times in the Environmental Room at 140 °F. This data would be good to compare with the existing data for asphalt-rubber blends with different carbonyl areas.

Experiment 2: Perform direct tension tests at several different strain rates in order to determine a better relationship between strain rate and failure properties. This would involve varying strain rates between 0.1mm/min and 1.0 mm/min. These would provide a good range of rates and it would also give data at the SHRP specified 1.0 mm/min strain rate for performance grading.

Experiment 3: Perform direct tension tests for asphalt-rubber blends with different rubber compositions, in order to better correlate the improved failure characteristics with rubber content. Blends should be made and tested that contain between five and twenty percent rubber. This would be helpful in determining whether the cost of extra rubber is worth the benefits gained from improved failure properties.

Experiment 4: Perform direct tension tests at various temperatures between -10 °C and -30 °C to allow for better determination of the temperature dependence of failure properties. These data could also be used to find the glass transition temperatures of various asphalts.

From these data, it can be concluded that increased rubber content, decreased amounts of aging, higher temperatures, and curing conditions that achieve a high degree of homogeneity all have positive effects on the failure properties of asphalt. Generally, these conditions decreased the stiffness relative to the unmodified asphalt, thereby increasing the failure strain and usually the failure stress. This research also shows that the addition of rubber to asphalt improves its low temperature properties, in many respects making these asphalts better suited for road use than asphalts without rubber. Asphalt-rubber blends could be used very extensively for road use in the future. This makes it important to understand what variables affect the performance of these asphalt blends. This research will help direct future research in the area of low temperature tensile properties of asphalts and help provide better performing, longer lasting roadways.

Literature Cited

Billiter, T.C., "Physical Properties of Asphalt-Rubber Binder" Texas A&M University (1995).

Bullin, J.A., Richard R. Davison, Charles J. Glover. *Asphalt Research Program*. Chemical Engineering Department, Texas A&M University (October 27, 1995).

Kennedy, T. W., G. A Huber, E.T Harrigan, R. J Comminsky, C. S Hughes, H. Von Quintus, and J.S. Moulthrop, *Superior Performing Asphalt Pavement - Superpave. The Product of the SHRP Asphalt Research Program*, Strategic Highway Research Program (1995), pg. 35.

"Model BTI-3 Direct Tensile Testing System for Asphalt Binder", Instron (1995), pp. 1-2

Appendices

Appendix A: Direct Tension Testing Procedure

This is a process description of the direct tension testing procedure used in the Center for Asphalt and Materials Chemistry at Texas A&M University. It is intended for ease in performing the test in the future and to increase repeatability in doing the direct tension test. By following the same procedure every time the results gathered from this test will be more accurately compared. The specific procedures of this test will be outlined as well as why these procedures are done the way they are. This information is provided as a building point for future improvements on the procedure of doing the direct tension test.

Major Process Steps

1. Preparation of the asphalt
2. Pouring the asphalt
3. Trimming the asphalt molds
4. Equilibration of temperature
5. Testing procedure and parameters
6. Maintenance

Preparation of the Asphalt

Asphalt samples are usually contained in small tins and labeled with the name and/or other description of the asphalt contained in them. The asphalt samples to be poured must be heated in a convection oven or on a hot plate in order to get them to a good pouring consistency. When heated to the proper temperature, the asphalt should have the consistency of 10W-30 motor oil, or in other words be liquid enough to pour easily. This takes varied amounts of time depending on the hardness of the asphalt and what additives are in the asphalt. Rubber asphalt blends and highly aged blends tend to take longer to heat than tank asphalts. If heating in a convection oven, the asphalt should be heated to 160 to 200 degrees C for about thirty minutes. No stirring of the asphalt samples is needed. On the other hand, if a hot plate is used, the samples must be stirred to provide even heating and to prevent the asphalt on the bottom from burning.

Pouring

Once the asphalt is at the correct consistency, it is ready to pour. The asphalt is poured in dogbone shaped silicon molds with plastic end pieces placed inside the molds for the asphalt to bond to (see Figure 9). The best results are achieved when the end pieces are tilted out of the molds about two millimeters to allow the asphalt to flow into the small corners. The molds should be heated on top of a thin metal plate by the hot plate for ten minutes . The asphalt should be poured while the mold is still hot. The mold should be resting on a flat surface while pouring. While holding the tin with a protective glove, the asphalt is poured by starting from one end of the mold and allowing it to fill up that end of the mold before proceeding. When the asphalt starts to reach the top of the mold, the

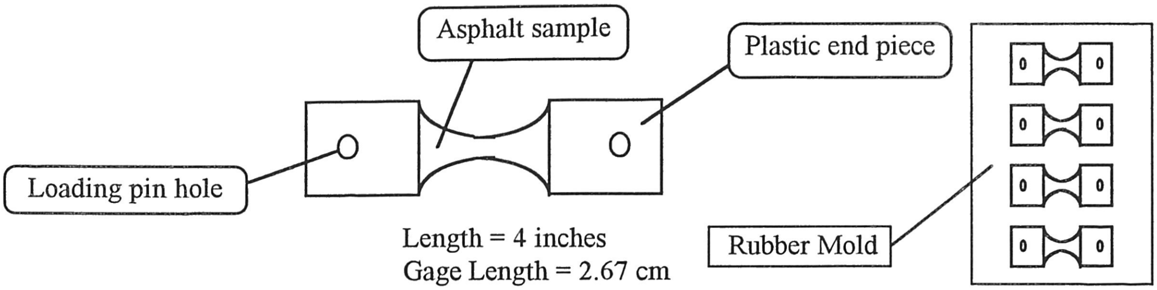


Figure 9. Asphalt Sample Bonded to End Pieces

person pouring must follow the flow of the asphalt towards the other end of the mold. This prevents air bubbles from being trapped in the asphalt. When the opposite end of the mold is reached the mold is continued to be filled until the asphalt fills the entire mold. It is best to get the asphalt as close to the top of the mold as possible without pouring in too little. After each sample is poured, the plastic end pieces should be pushed into place. The entire pouring process should take no longer than 10 seconds per specimen. If too much time is taken, the asphalt will cool down too much and become too thick to pour. When all of the molds are poured, they must cool down for 45 minutes to an hour before they are trimmed.

Trimming

When the asphalt specimens have cooled for a sufficient amount of time, they must be trimmed to the correct size. This is done by first placing the mold into an aluminum trimming plate. The top of the plate surface should be even with the top of the mold. A thick spatula that is at least as wide as the mold should be used in trimming. The spatula should be heated with a Bunsen burner or a convection oven before it is used in trimming. The asphalt is trimmed by running the spatula along the top of the trimming plate and taking off any asphalt that overflowed the molds. The spatula must be kept hot while trimming and much care must be taken to insure that the specimens are not damaged. Trimmed asphalt is usually saved and put back into the original tins. In order to get rid of any streaks on the asphalt samples a heat gun is used on the low setting to re-melt the tops of each sample. When all samples have been trimmed, they must cool down for five to ten minutes to make sure they do not deform during moving.

Equilibration of Temperature

The next step in the direct tension testing procedure is to equilibrate the temperature of the samples to the testing temperature. First, the samples must be carefully taken out of the molds one at a time. A specimen is taken out of the rubber molds by bending the mold slightly and then ‘popping’ it out. Care must be taken that the other samples in the same mold are not damaged while this is done. The de-molded sample is then held vertically by one of the plastic end pieces and then placed in a two piece aluminum frame that holds the shape of the specimen. This is then lowered into an ethanol bath at the testing temperature with the use of tongs. After fifteen to thirty seconds in the bath the aluminum frame pieces are removed. The cold bath temperatures, usually between -12 and -24 degrees C, will make the asphalt rigid and it will continue to hold its shape. Other asphalt samples are placed in the bath at five to ten minute intervals because of the strict time requirements of temperature equilibration. The five to ten minute intervals between samples allows for the time to run the experiment and get the next sample prepared to run. More time between samples should be allowed when testing at the high end of the temperature range because the samples take longer to break. The asphalt samples must stay in the bath for one hour +/- ten minutes before they are tested.

Testing Procedure and Parameters

The direct tension test itself is done on an Instron model BTI-3 Direct Tension Testing System (DTTS). The testing apparatus consists of an actuator, load cell, and loading pins, all of which are submersed in the temperature controlled ethanol bath. The temperature is controlled by a recirculating cooler that can deliver temperatures down to -40 degrees C and a temperature stability of +/- 0.2 degrees C (Instron 1995). The bath takes about ten minutes to equilibrate down to a lower temperature and longer to warm up to a higher temperature. If more than one testing temperature is to be used in one day the higher temperature should be tested first. The Strategic Highway Research Program (SHRP) grades asphalts at temperatures of -6, -12, -18, -24, -30 and -36 degrees C. Most tests are run at -12, -18, and -24 degrees C. Before the samples are ready to be tested, the data acquisition software must be run. This consists of windows based software that allows the user to collect data on the tests and observe real-time plots of the test. Data of interest in a direct tension test includes the stress, or load on the asphalt, the percent strain, or percent change in length over original length, and the energy required to break the sample. The software generates stress vs. strain curves while the test is being run (see Figure 1).

The actual test is begun by placing a sample on the loading pins. The loading pins are configured horizontally for easy placement into the holes located in the plastic end pieces on each specimen. A vernier control is located on a manual control panel and is used to get the pins in exact alignment with the holes. The specimen protect is then activated via the control panel to prevent the sample from being damaged in preloading. The sample is preloaded with two Newtons of force to get all of the 'slack' out of it. Next, the gauge length and the strain are reset by pushing the two corresponding buttons on the control panel. When the force relaxes naturally down to about 0.95 Newtons, the 'Start Test' button is pushed to begin the test. The test itself consists of subjecting the sample to a constant rate of strain. SHRP specifies a 1 mm/min strain rate but the tests run were performed at a rate of 0.1 mm/min. This is done until the sample fails, usually when it breaks in half. The corresponding stress and strain at failure are called the failure stress and failure strain. Ductile failure occurs when the sample can no longer hold a load, but is not brittle enough to break. The failure stress is the maximum stress the sample can withstand in ductile failure. The Instron DTTS can produce loads up to 500 Newtons, or 100 pounds (Instron 1995). In order for the specimen to pass SHRP specifications at each temperature, the asphalt must fail at greater than 1% strain. When the sample breaks, the test is ended, the data is saved, and the next specimen is prepared for testing.

Maintenance

When all of the samples have been tested, the DTTS must be cleaned and prepared for the next time it will be used. All of the used asphalt is broken off of the plastic end pieces and placed back in the tins for re-use. The temperature controller should be set to -6 degrees C for storage because ethanol is highly flammable at room temperature. The plastic inserts are cleaned using varsol, which is similar to paint thinner, and then washed with soap and water. Most of the asphalt on the rubber molds is easily scraped off using a small spatula because these molds are made of a non-stick material. Masking tape is used to pull of any left over asphalt on the molds. The ethanol bath does not need to be cleaned after every test, and can be re-used many times. Current lab procedure allows for the computer to be left on, but the Instron control program should be exited.

Performing a similar and correct procedure in doing the direct tension test is very important. Repeatability is very hard to obtain in fracture testing and it is essential that every part of the preparation is done carefully. Any flaw made by air bubbles or small nicks in the asphalt will result in poor repeatability and therefore the fracture strength of the asphalt cannot be accurately determined. It is also necessary that these tests be done the same every time. This procedure is the current one used and recommended by the Texas Department of Transportation and the Strategic Highway Research Program. By using the correct procedures in preparing the samples, in temperature equilibration and in the actual testing, results from these tests can be more readily compared to data collected at other research facilities. This is very important in validating results and coming to conclusions that can be verified. Therefore, the outlined procedure for performing the direct tension test should be followed by all persons involved in doing research in this area.

Appendix B: Direct Tension Data

SHRP Core 8 Asphalts

Temp, C	Sample Name	Failure Stiffness, kg/cm^2	Failure Stress, kg/cm^2	Failure Strain, %
-10	AAD-1	433.619	4.855	1.1196
-10	AAD-1	370.502	5.471	1.4767
-10	AAM-1	804.679	13.035	1.6199
-10	AAM-1	718.869	13.757	1.9137
-10	AAM-1	708.086	14.292	2.0184
-10	AAM-1	658.495	15.767	2.3944
-18	AAB-1	1852.040	6.831	0.4135
-18	AAB-1	1914.010	7.775	0.4494
-18	AAB-1	2232.195	8.142	0.4671
-18	AAB-1	2232.521	8.752	0.4859
-18	AAD-1	2006.000	5.939	0.3782
-18	AAD-1	2054.500	6.634	0.4184
-18	AAD-1	1597.400	5.068	0.3603
-18	AAD-1	1901.800	6.734	0.4415
-18	AAG-1	3998.800	7.977	0.1850
-18	AAG-1	3999.600	3.771	0.0905
-18	AAG-1	3680.700	6.714	0.1677
-18	AAG-1	3944.000	4.122	0.1027
-18	AAM-1	2242.900	7.689	0.3688
-18	AAM-1	2475.600	10.328	0.4590
-18	AAM-1	2307.500	16.127	0.8441
-18	AAM-1	2238.200	11.569	0.5260
-18	AAF-1	2767.373	9.279	0.3353
-18	AAF-1	3025.401	4.526	0.1496
-18	AAF-1	2955.107	5.266	0.1782
-18	AAF-1	3109.812	4.786	0.1539

Exxon AC-10 Based Silverson Blends

Temp, C	Sample Name	Failure Stiffness, kg/cm^2	Failure Stress, kg/cm^2	Failure Strain, %
-18	Silv. Standard	908.471	15.444	1.7000
-18	Silv. Standard	956.996	11.394	1.1906
-18	Silv. Standard	1103.613	11.056	1.0018
-18	Silv. Standard	1110.379	12.132	1.0926
-18	Silv. 8000rpm	940.138	13.632	1.4500
-18	Silv. 8000rpm	904.751	16.091	1.7785
-18	Silv. 8000rpm	903.013	13.938	1.5435
-18	Silv. 8000rpm	840.709	15.216	1.8099
-18	Silv. TG -40	942.463	13.923	1.4773
-18	Silv. TG -40	877.560	14.399	1.6408
-18	Silv. TG -40	1160.995	9.245	0.7963
-18	Silv. TG -40	1126.751	10.214	0.9065
-18	Silv. 450 F	1049.961	5.380	0.5124
-18	Silv. 450 F	975.039	5.664	0.5809
-18	Silv. 450 F	1054.720	5.050	0.4788
-18	Silv. 450 F	1033.248	4.817	0.4662
-18	Silv 20% rubber	348.742	13.067	3.7469
-18	Silv 20% rubber	400.000	12.556	3.1390
-18	Silv 20% rubber	364.453	13.667	3.7500
-18	Silv 20% rubber	371.360	13.926	3.7500
-18	Silv 20% rubber	562.380	18.094	3.2174
-18	Silv 20% rubber	405.253	14.842	3.6624
-18	Silv 20% rubber	539.420	14.669	2.7194
-18	Silv 20% rubber	431.952	16.101	3.7275
-18	Exxon AC-10 - Neat	1715.315	6.664	0.3885
-18	Exxon AC-10 - Neat	1593.852	7.778	0.4880
-18	Exxon AC-10 - Neat	1660.812	7.565	0.4555
-18	Exxon AC-10 - Neat	1518.489	3.819	0.2515
-18	S1 Std. unaged	797.135	10.963	1.3753
-18	S1 Std. unaged	939.955	9.170	0.9756
-18	S1 Std. unaged	432.373	16.214	3.7500
-18	S1 Std. unaged	657.328	12.294	1.8703
-18	S1 Std. unaged	776.256	10.200	1.3140
-18	S1 Std. unaged	651.860	11.740	1.8010
-18	S1 Std. unaged	424.347	15.913	3.7500
-18	S1 Std. 140F aged	1648.741	11.068	0.6713
-18	S1 Std. 140F aged	1872.110	7.612	0.4066
-18	S1 Std. 140F aged	1795.386	8.871	0.4941
-24	Silv. Standard	2158.334	21.197	0.9821
-24	Silv. Standard	2231.856	20.542	0.9204
-24	Silv. Standard	2032.638	18.995	0.9345
-24	Silv. Standard	2269.592	15.726	0.6929
-24	Silv. 8000rpm	2238.157	15.450	0.6903
-24	Silv. 8000rpm	2088.510	25.956	1.2428
-24	Silv. 8000rpm	2020.742	31.370	1.5524
-24	Silv. TG -40	1749.469	12.360	0.7065
-24	Silv. TG -40	2370.123	17.008	0.7176
-24	Silv. TG -40	2166.577	20.043	0.9251
-24	Silv. 450 F	1834.531	12.506	0.6817
-24	Silv. 450 F	1852.938	15.359	0.8289
-24	Silv. 450 F	1872.989	15.248	0.8141
-24	Silv. 450 F	1791.451	10.059	0.5615

Exxon AC-10 Based Silverson Blends

Temp, C	Sample Name	Failure Stiffness, kg/cm^2	Failure Stress, kg/cm^2	Failure Strain, %
-24	Silv 20% rubber	1124.658	8.228	0.7316
-24	Silv 20% rubber	1124.184	5.341	0.4751
-24	Silv 20% rubber	902.191	7.988	0.8854
-24	Silv 20% rubber	1171.295	6.031	0.5149
-24	Silv 20% rubber	1699.965	14.567	0.8569
-24	Silv 20% rubber	2008.970	13.438	0.6689
-24	Silv 20% rubber	2401.134	14.402	0.5998
-24	Silv 20% rubber	1948.945	9.887	0.5073
-24	Silv 20% rubber	2128.722	9.724	0.4568
-24	Silv 20% rubber	2134.023	10.525	0.4932
-24	Silv 20% rubber	1990.810	14.081	0.7073
-24	Exxon AC-10 - Neat	3220.674	4.393	0.1364
-24	Exxon AC-10 - Neat	3130.761	5.842	0.1866
-24	Exxon AC-10 - Neat	3085.357	4.446	0.1441
-24	Exxon AC-10 - Neat	2971.185	2.784	0.0937
-24	S1 Std. unaged	2145.035	20.262	0.9446
-24	S1 Std. unaged	2353.255	7.048	0.2995
-24	S1 Std. unaged	2637.939	5.785	0.2193
-24	S1 Std. unaged	2327.072	12.054	0.5180
-24	S1 Std. unaged	2370.029	11.561	0.4878
-24	S1 Std. unaged	2235.093	9.783	0.4377
-24	S1 Std. unaged	2729.989	10.232	0.3748
-24	ExS1 20% unaged	1152.767	15.205	1.3190
-24	ExS1 20% unaged	1126.562	18.657	1.6561
-24	ExS1 20% unaged	1423.188	13.331	0.9367
-24	ExS1 20% unaged	923.546	17.890	1.9371
-30	Silv. 8000 rpm	2122.275	7.203	0.3394
-30	Silv. 8000 rpm	2234.241	3.119	0.1396
-30	Silv. 8000 rpm	1892.908	5.285	0.2792
-30	Silv. 8000 rpm	2293.827	7.432	0.3240

Fina AC-5 Based Silverson Blends

Temp, C	Sample Name	Failure Stiffness, kg/cm^2	Failure Stress, kg/cm^2	Failure Strain, %
-18	Silv. Standard	1517.099	9.937	0.6550
-18	Silv. Standard	1330.953	10.066	0.7563
-18	Silv. Standard	1541.613	17.721	1.1495
-18	Silv. Standard	630.192	25.167	2.8120
-18	Silv. 8000rpm	1374.420	19.685	1.8311
-18	Silv. 8000rpm	1205.046	14.328	1.1890
-18	Silv. 8000rpm	989.290	22.816	2.3063
-18	Silv. 8000rpm	1412.547	14.658	1.0377
-18	Silv. TG -40	1070.161	14.780	1.3811
-18	Silv. TG -40	1514.807	7.468	0.4930
-18	Silv. TG -40	1007.313	16.805	1.6683
-18	Silv. TG -40	1103.485	15.451	1.4002
-18	Silv. 450 F	721.995	11.466	1.5881
-18	Silv. 450 F	656.723	13.055	1.9879
-18	Silv. 450 F	574.044	14.831	2.5836
-18	Silv. 450 F	705.959	13.553	1.9198
-18	Silv 20% rubber	429.754	11.526	2.6820
-18	Silv 20% rubber	344.373	12.914	3.7500
-18	Silv 20% rubber	706.176	21.907	3.1022
-18	Silv 20% rubber	475.280	16.977	3.5720
-18	FDR Neat (PAV)	1676.913	16.039	0.9565
-18	FDR Neat (PAV)	2194.267	6.469	0.2948
-18	FDR Neat (PAV)	1816.116	8.632	0.4753
-18	FDR Neat (PAV)	1868.130	13.104	0.7015
-18	Silv. Std. unaged	400.133	15.005	3.7500
-18	Silv. Std. unaged	692.663	23.119	3.3377
-18	Silv. Std. unaged	962.079	26.233	2.7267
-18	Silv. Std. unaged	1235.543	16.922	1.3696
-18	Silv. Std. unaged	424.358	14.934	3.5192
-18	Silv. Std. unaged	828.709	18.815	2.2704
-18	Silv. Std. unaged	588.847	20.400	3.4644
-18	Silv. Std. 140F aged	2255.318	6.743	0.2990
-18	Silv. Std. 140F aged	1991.997	9.209	0.4623
-18	Silv. Std. 140F aged	1677.534	13.739	0.8190
-18	Silv. Std. 140F aged	1865.202	8.742	0.4687
-24	Silv. Standard(PAV)	2249.103	24.450	1.0871
-24	Silv. Standard(PAV)	2653.517	21.053	0.7934
-24	Silv. Standard(PAV)	2828.623	20.516	0.7253
-24	Silv. 8000rpm	2237.259	11.589	0.5180
-24	Silv. 8000rpm	2633.803	24.684	0.9372
-24	Silv. 8000rpm	2668.721	20.357	0.7628
-24	Silv. TG -40	2647.576	16.550	0.6251
-24	Silv. TG -40	3062.440	12.850	0.4196
-24	Silv. TG -40	3062.629	13.399	0.4375
-24	Silv. TG -40	2926.566	16.260	0.5556
-24	Silv. 450 F	2418.921	16.901	0.6987
-24	Silv. 450 F	2778.511	5.896	0.2122
-24	Silv. 450 F	2466.479	19.241	0.7801
-24	Silv. 450 F	3242.580	5.681	0.1752
-24	Silv. 20% rubber	1400.917	16.804	1.1995
-24	Silv. 20% rubber	1894.616	23.084	1.2184
-24	Silv. 20% rubber	2206.860	14.733	0.6676
-24	Silv. 20% rubber	2192.956	13.013	0.5934
-24	Silv. Std. unaged	1650.978	22.800	1.3810
-24	Silv. Std. unaged	2392.442	14.814	0.6192
-24	Silv. Std. unaged	2409.887	11.700	0.4855

Specialty Asphalts

Temp, C	Sample Name	Failure Stiffness, kg/cm^2	Failure Stress, kg/cm^2	Failure Strain, %
-18	Fina F7 Mix	2130.492	8.147	0.3824
-18	Fina F7 Mix	2559.524	4.945	0.1932
-18	Fina F7 Mix	1942.132	7.652	0.3940
-18	Fina F7 Mix	2107.486	3.294	0.1563
-24	Exxon/Sun AC-5	2578.733	8.876	0.3442
-24	Exxon/Sun AC-5	2484.902	5.596	0.2252
-24	Exxon/Sun AC-5	2636.470	9.051	0.3433
-24	Exxon/Sun AC-5	2468.042	14.480	0.5867
-24	Neste Wright	1887.221	11.804	0.6255
-24	Neste Wright	1757.393	9.556	0.5438
-24	Neste Wright	1976.099	12.964	0.6560
-18	NW unaged	348.453	13.067	3.7500
-18	NW unaged	402.036	12.517	3.1134
-18	NW unaged	364.373	13.664	3.7500
-18	NW unaged	371.360	13.926	3.7500

Appendix C: Error Reduction

The direct tension testing procedure required great care to be taken in order to be able to achieve good reproducibility of data and become proficient at performing the direct tension tests. These are some of the problems that occurred and were overcome:

Problem 1: The asphalt was not flowing into the small corners of the dogbone shaped molds and therefore gave poor results because of premature fracture.

Solution 1: In order to get good molds I began tilting the plastic end pieces out of the mold slightly so the asphalt can flow into the corners. I then slide the end pieces back into the normal position immediately after each mold is poured.

Problem 2: Air bubbles trapped in the asphalt gave poor results because of premature fracture of the samples.

Solution 2: While heating the samples, I began to limit stirring them until the asphalt becomes runny. This prevents air bubbles from being trapped in the thick asphalt when the samples are stirred. The asphalt samples were also heated in a convection oven which heated the samples much more evenly than a hot plate and allowed for a minimum amount of stirring. With practice I also became better at pouring the molds in a smooth motion without trapping air bubbles.

Problem 3: Difficulty in trimming the samples without damaging them.

Solution 3: Again, with practice I was able to get much better at trimming the samples even without the use of the proper molds for the trimming plate, which have yet to arrive. Once they do arrive trimming will be even more easy.

Problem 4: There is a limited amount of each sample available, and there was a concern that re-using the samples would affect their properties significantly.

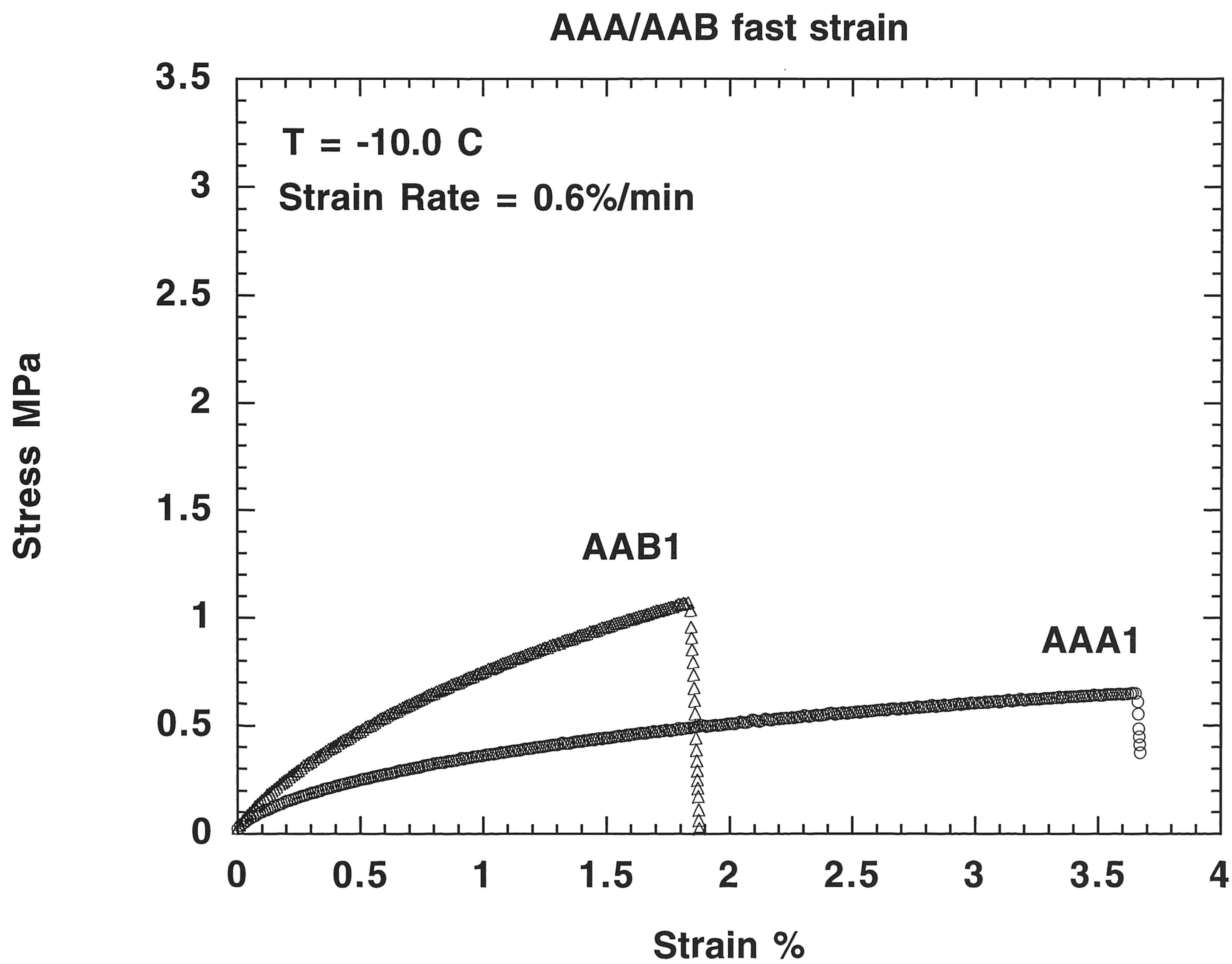
Solution 4: I ran a direct tension test on a sample of new AAG-1 and then the next week I re-ran the same asphalt that had undergone the direct tension test. I found no significant differences in the results of these two or when other samples had been re-tested. Therefore, I concluded that there is no significant affect on the fracture or other low temperature properties of the asphalt when it undergoes the direct tension test.

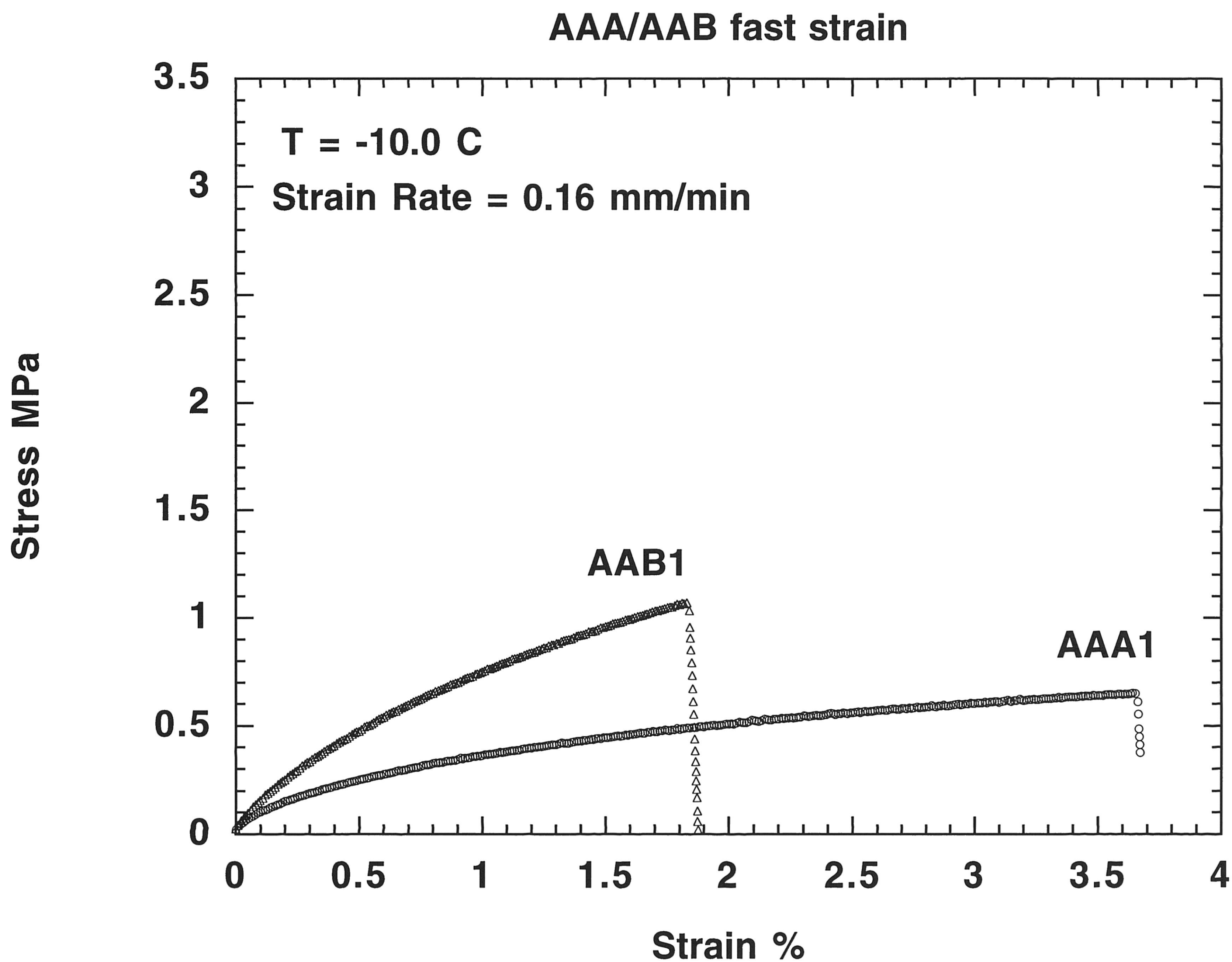
Problem 5: The trimming spatula was making small streak marks on the top of the asphalt samples which could lead to minor cracks and stress centers that cause premature fracture.

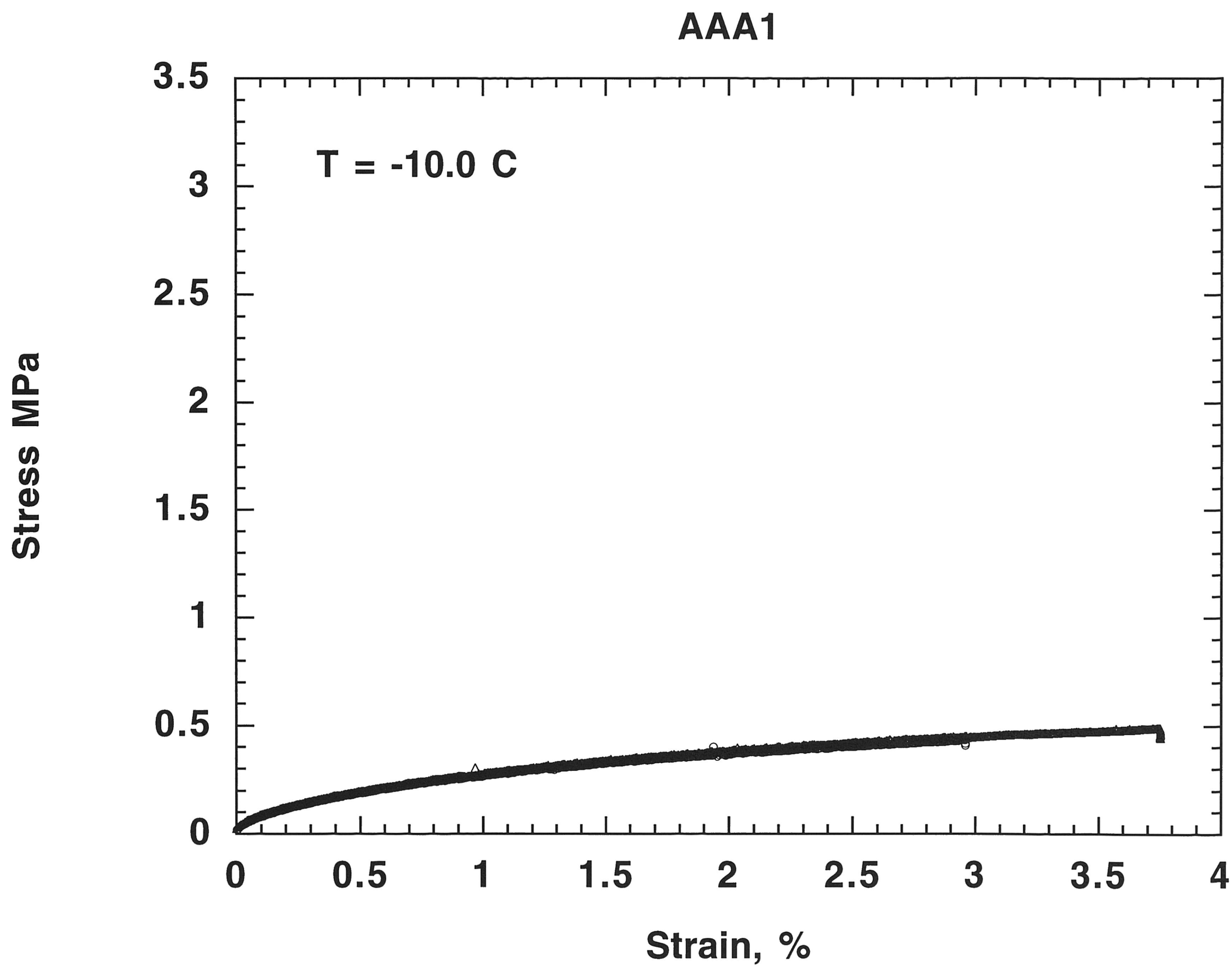
Solution 5: A heat gun on the low setting was used to anneal the top of the dogbone specimens and eliminate the streak marks.

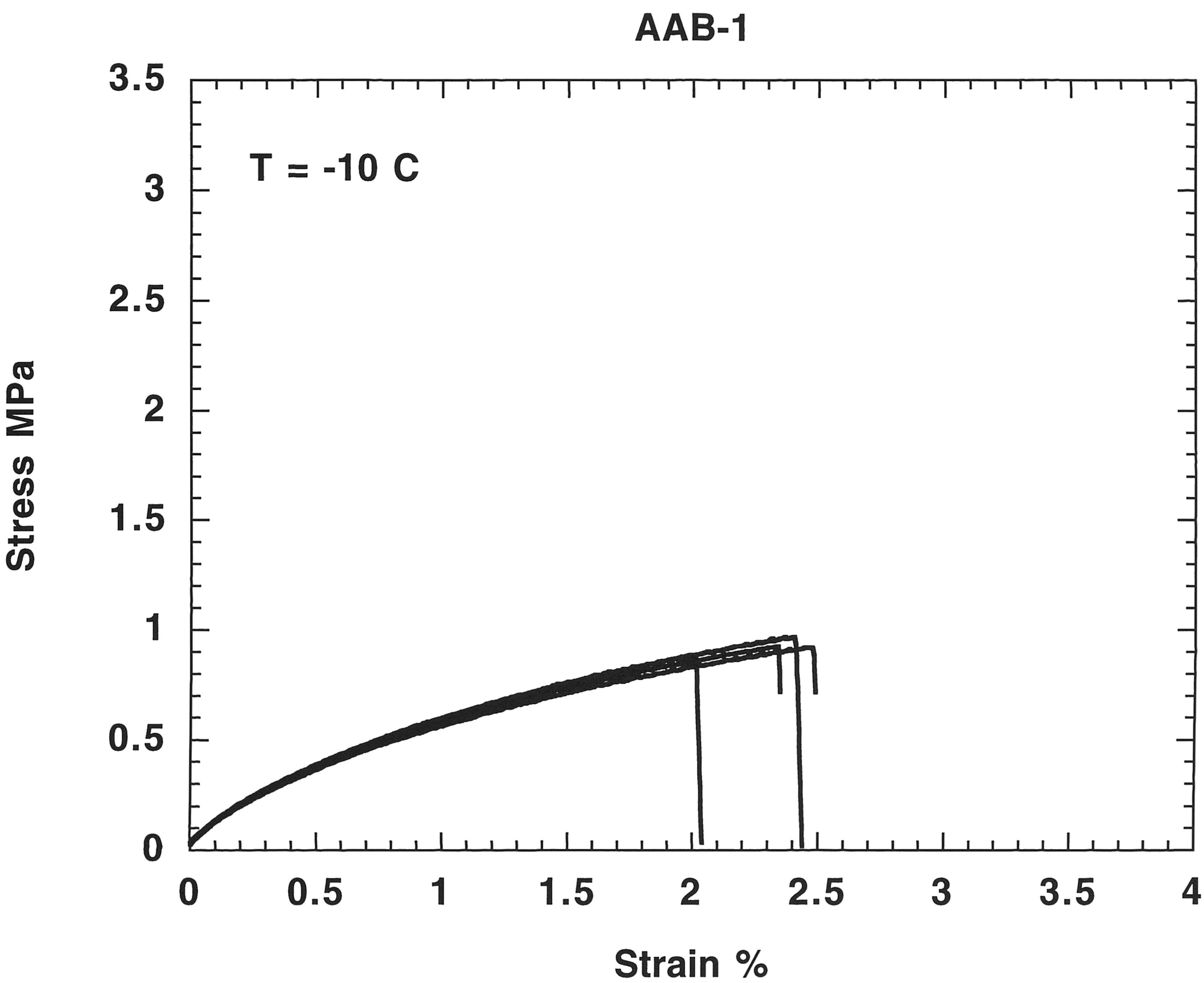
There was still significant scatter in the failure strain of the various samples. Other preventable variables may be involved or this scatter may be unavoidable because of the inherent sensitivity of fracture properties.

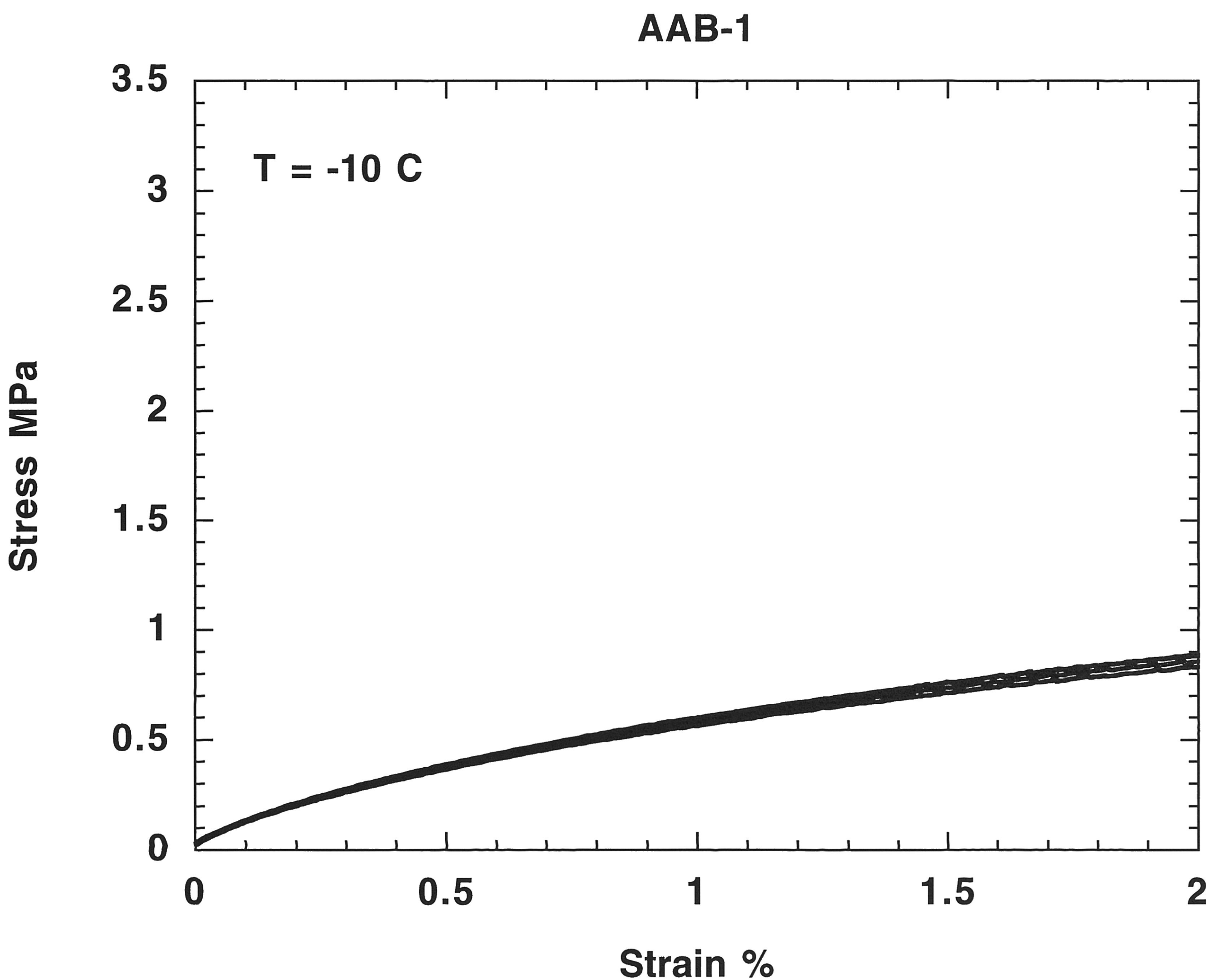
Appendix D: SHRP Core Stress-Strain Curves

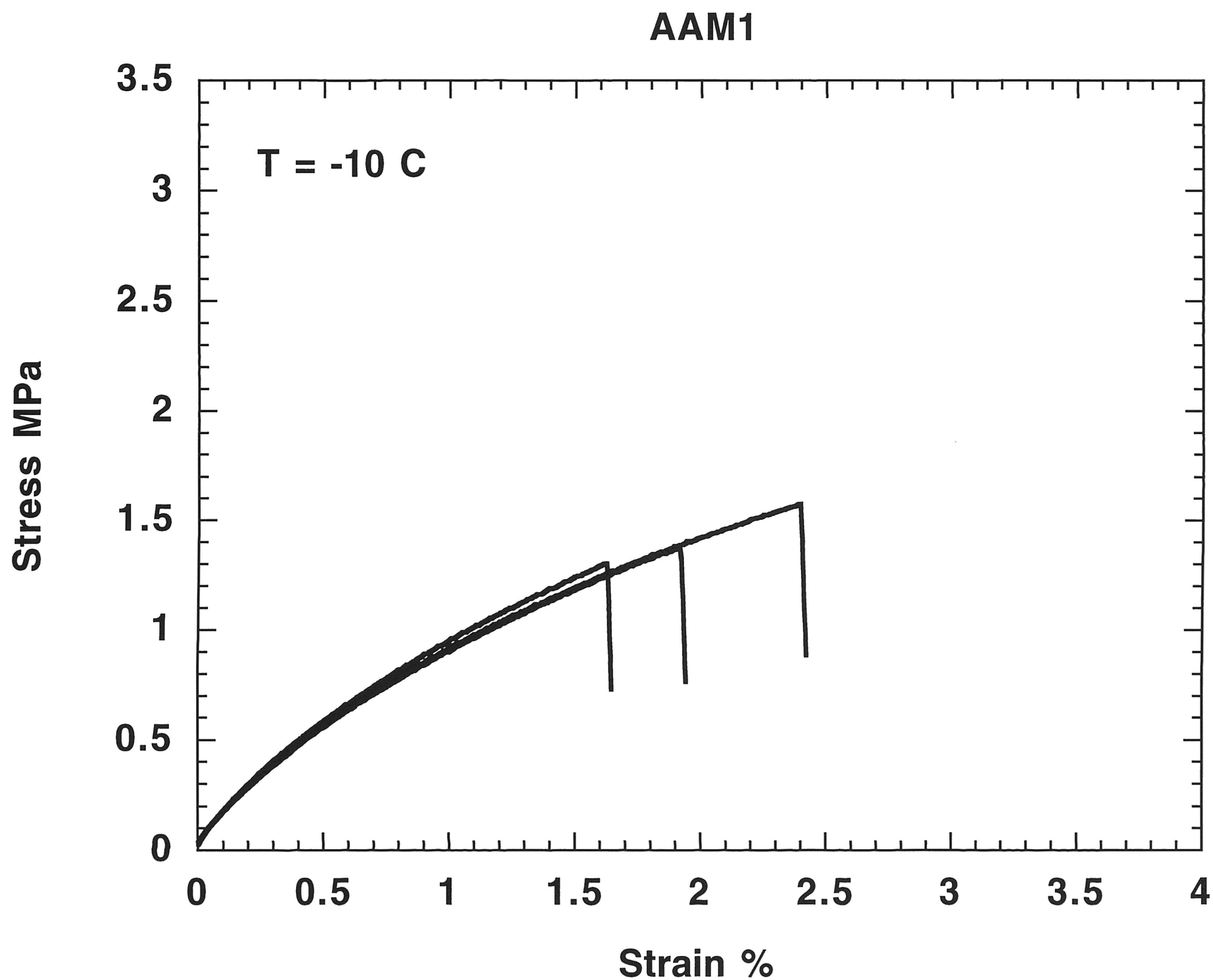

AAA/AAB fast strain
T = -10.0 C
Strain Rate = 0.6%/min
AAB1
AAA1
Stress MPa
Strain %
0
0.5
1
1.5
2
2.5
3
3.5
4

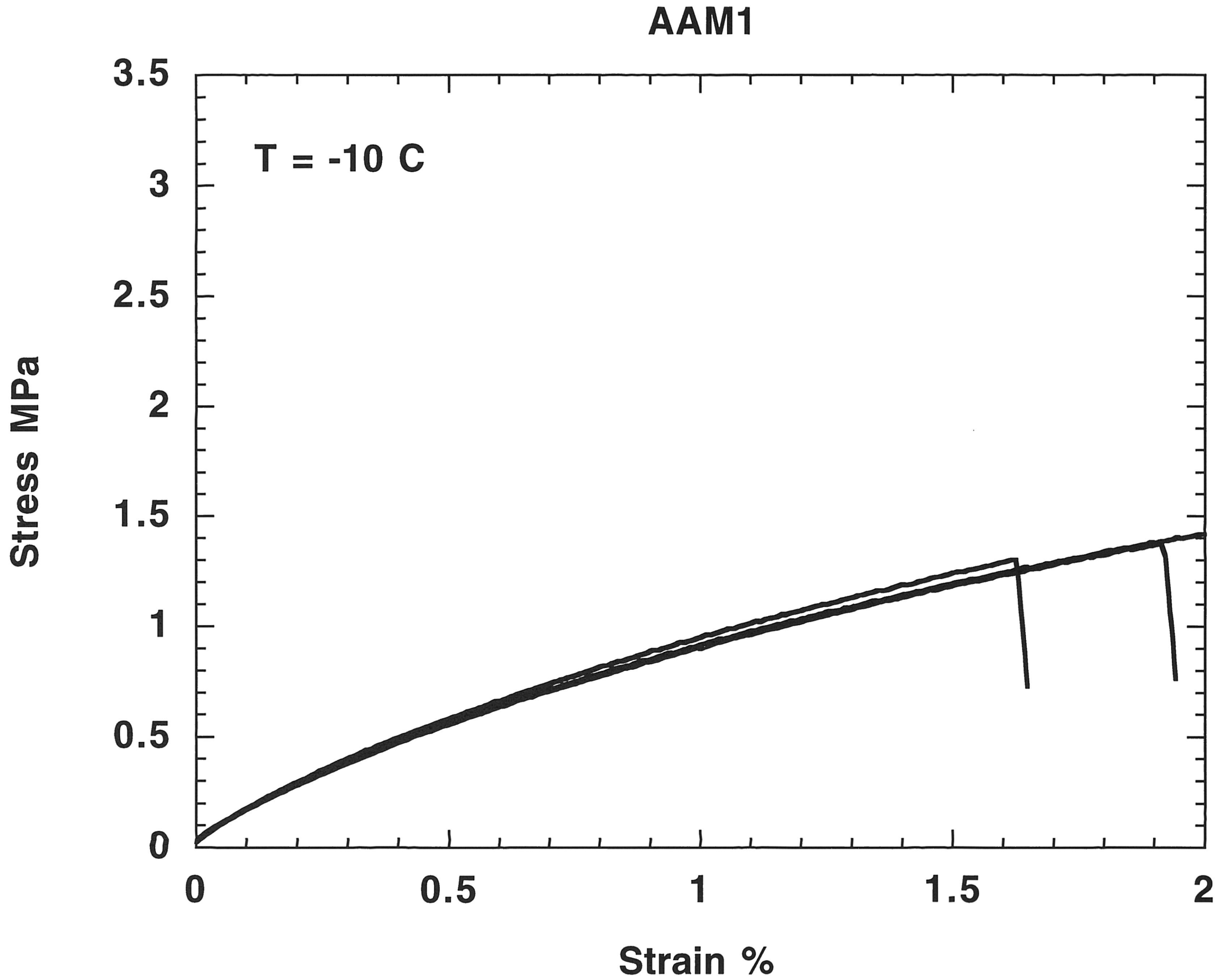

AAA/AAB fast strain
T = -10.0 C
Strain Rate = 0.16 mm/min
AAB1
AAA1
Stress MPa
Strain %
0
0.5
1
1.5
2
2.5
3
3.5
4

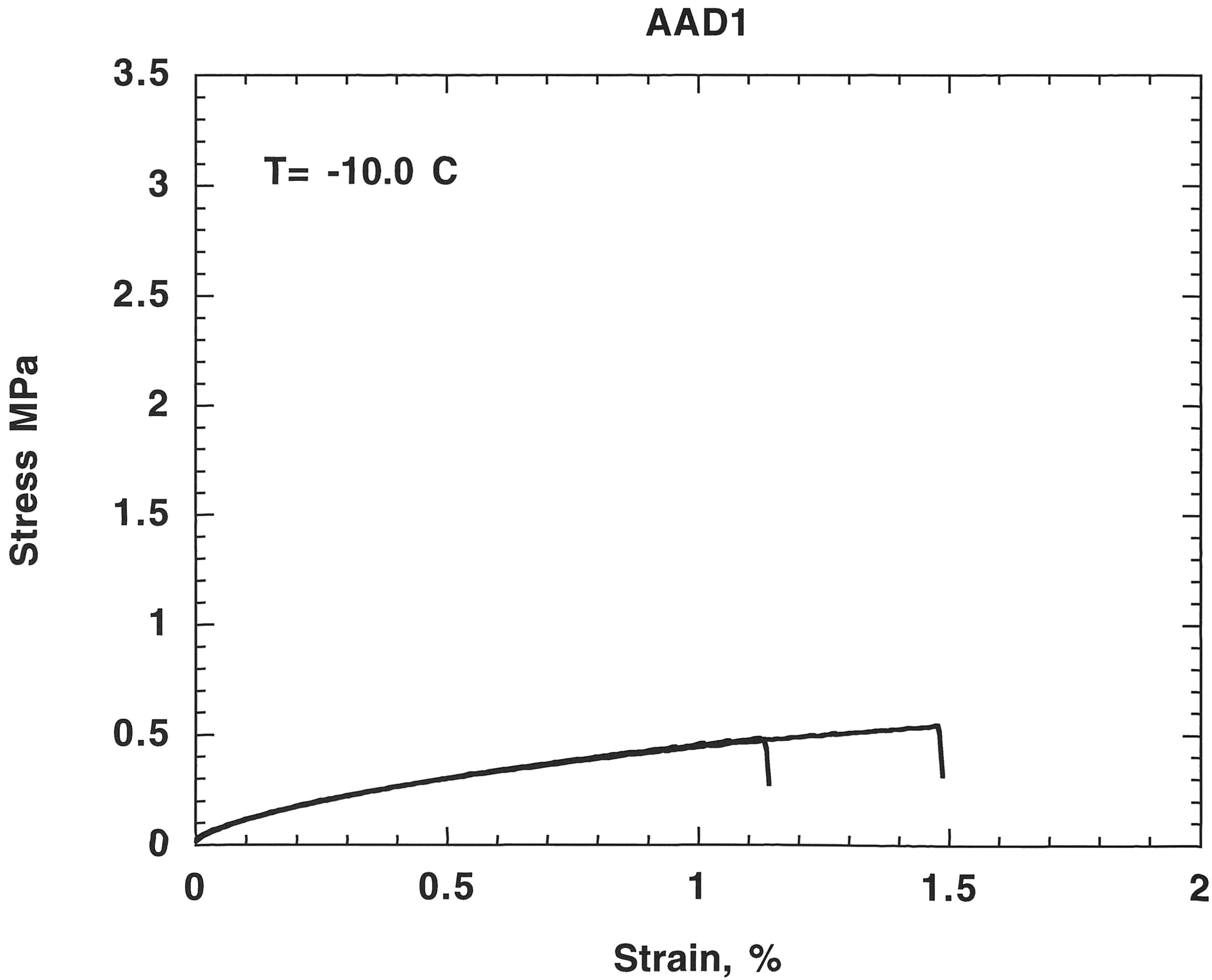

AAA1
T = -10.0 C
Stress MPa
Strain, %
0
0.5
1
1.5
2
2.5
3
3.5
4


AAB-1
T = -10 C
Stress MPa
Strain %
3.5
3
2.5
2
1.5
1
0.5
0
0
0.5
1
1.5
2
2.5
3
3.5
4

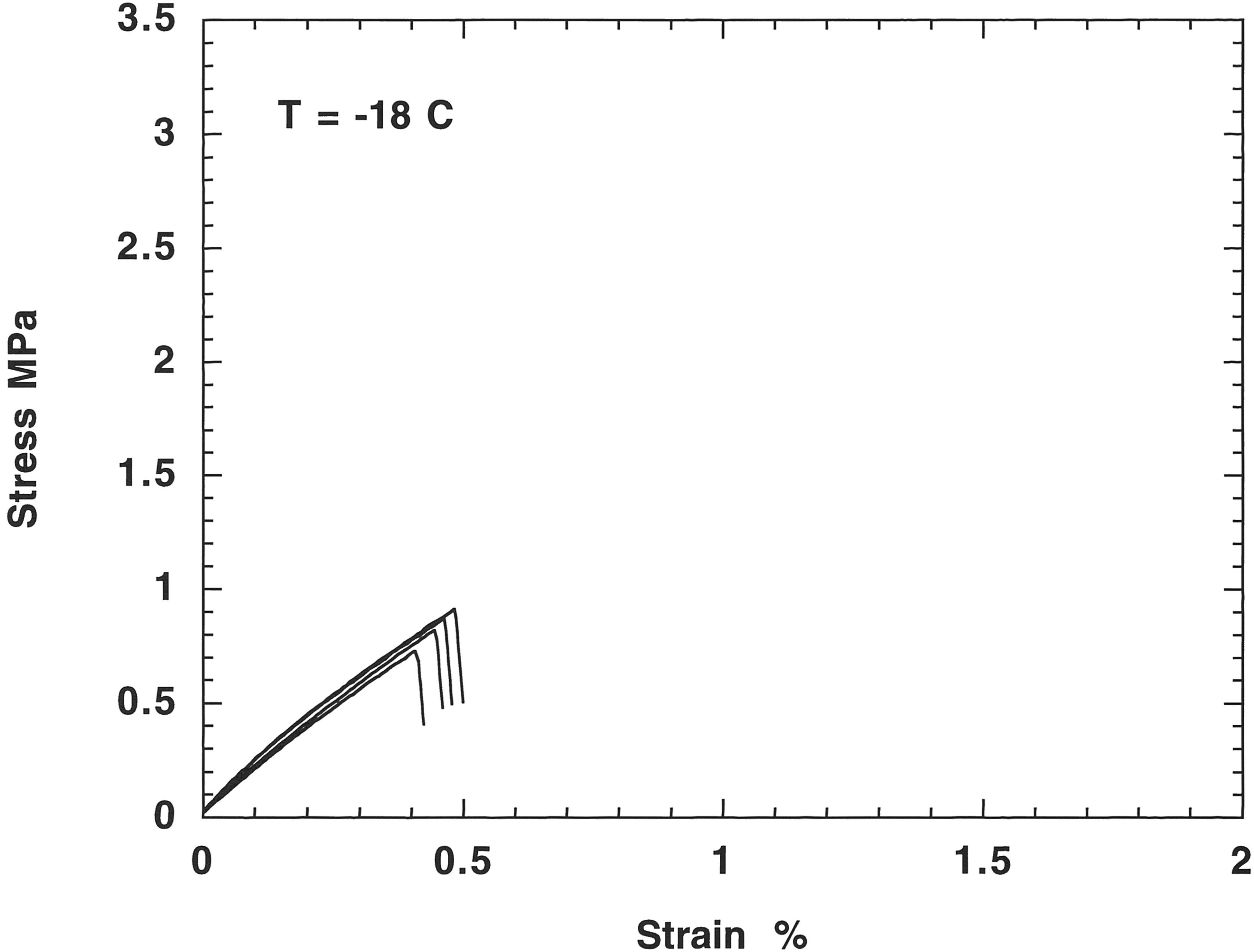

AAB-1
T = -10 C
Stress MPa
Strain %
0
0.5
1
1.5
2
2.5
3
3.5
0
0.5
1
1.5
2

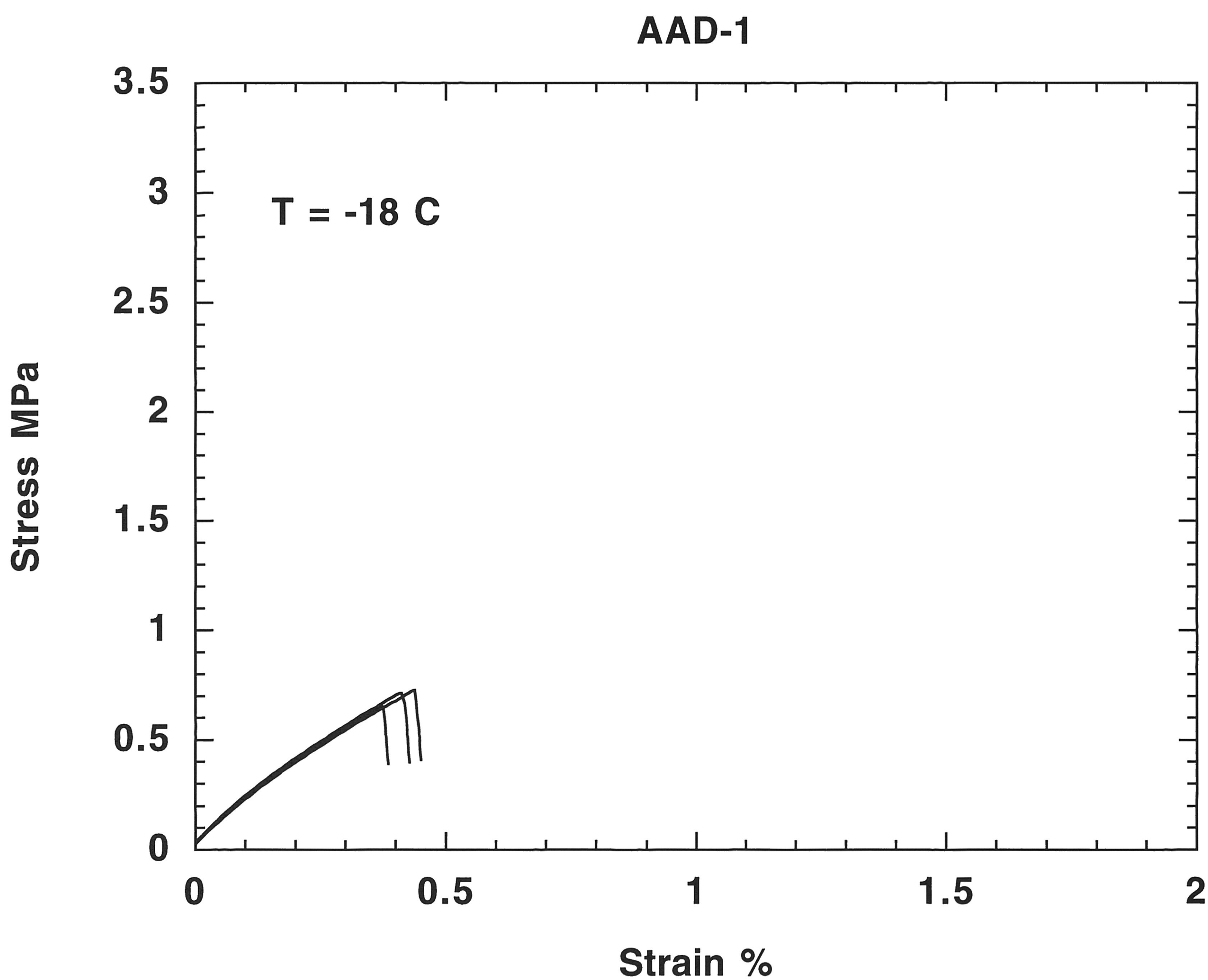

AAM1
T = -10 C
Stress MPa
Strain %
3.5
3
2.5
2
1.5
1
0.5
0
0
0.5
1
1.5
2
2.5
3
3.5
4

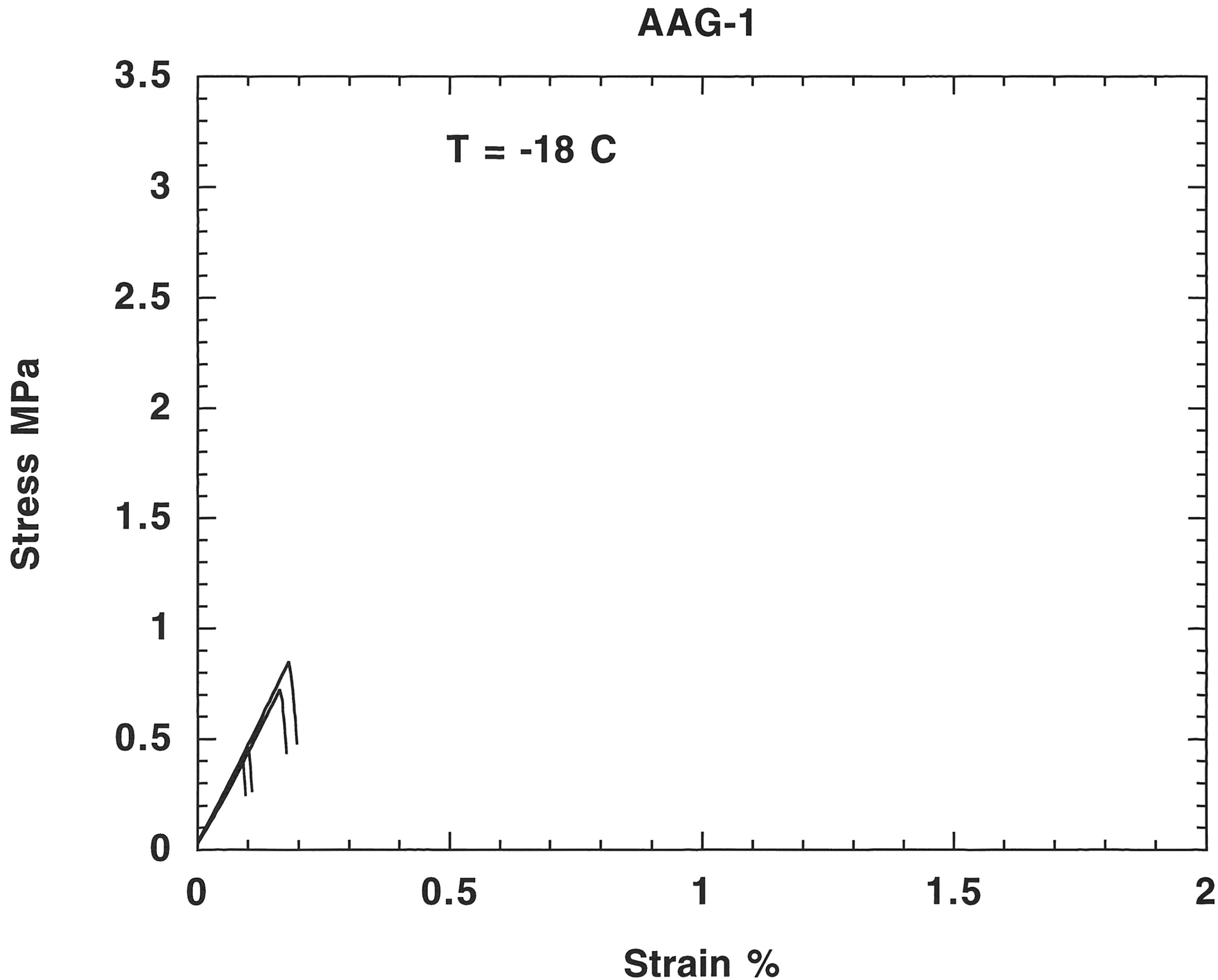

AAM1
T = -10 C
Stress MPa
3.5
3
2.5
2
1.5
1
0.5
0
0
0.5
1
1.5
2
Strain %

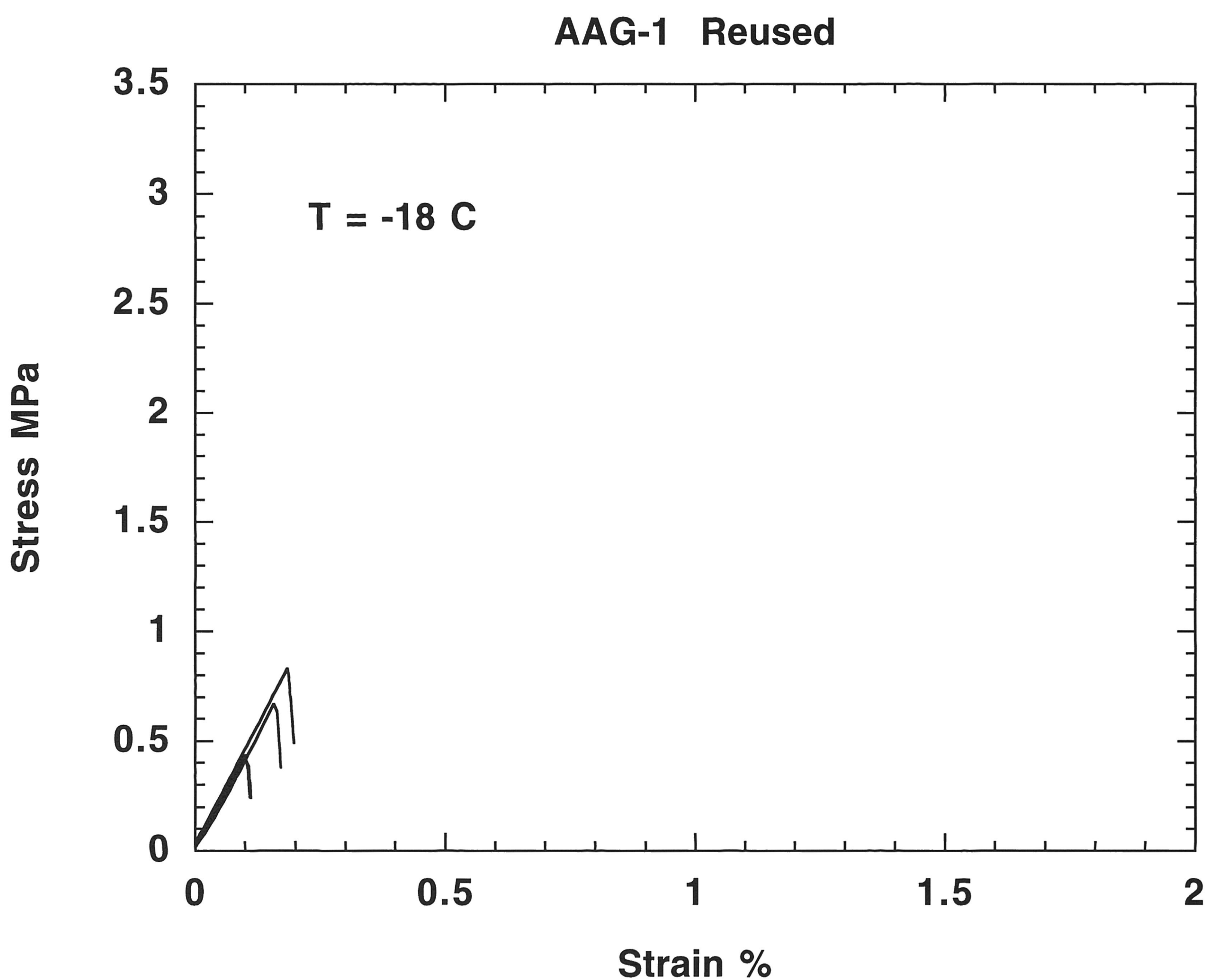

AAD1
T= -10.0 C
Stress MPa
3.5
3
2.5
2
1.5
1
0.5
0
0
0.5
1
1.5
2
Strain, %

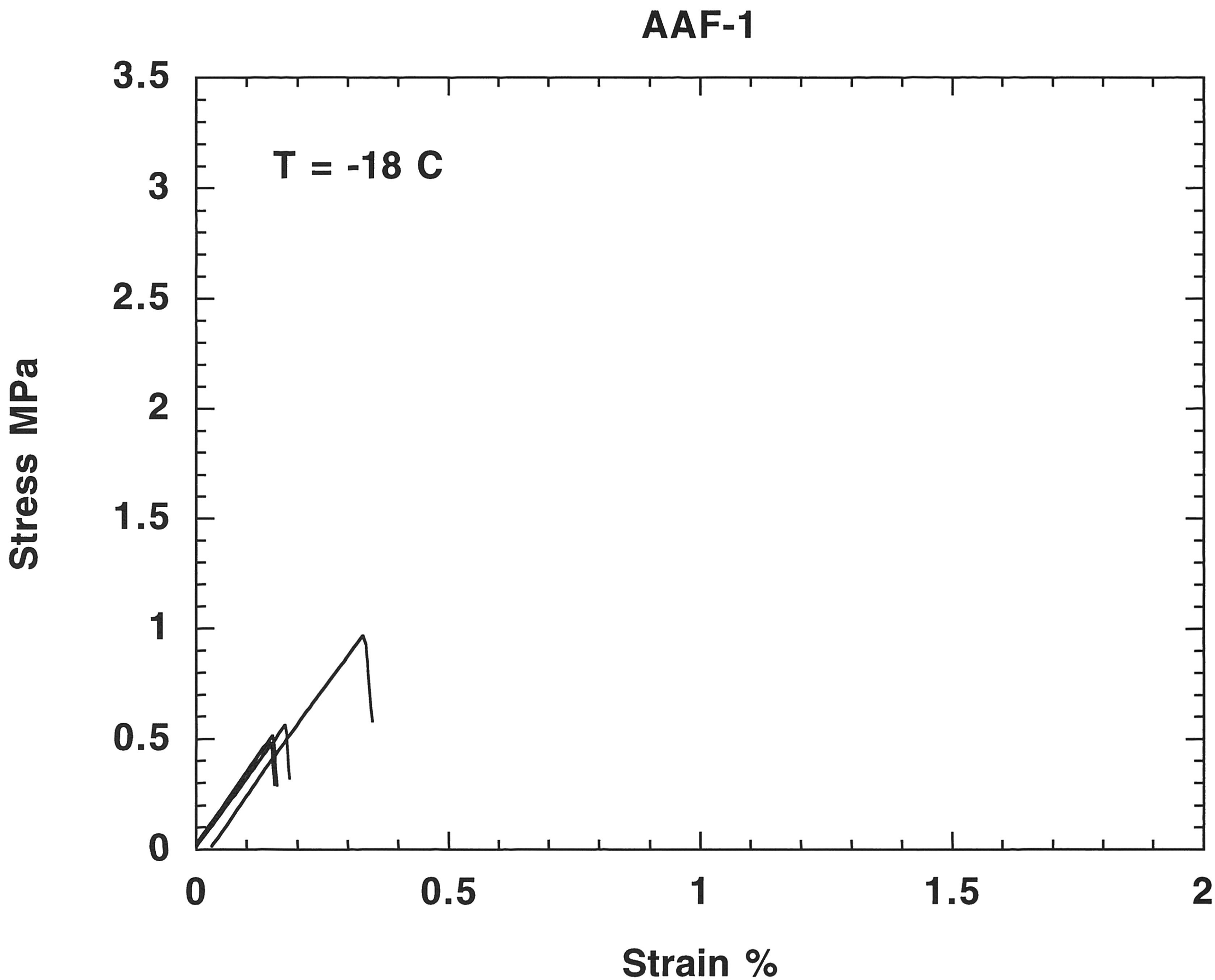
AAB-1

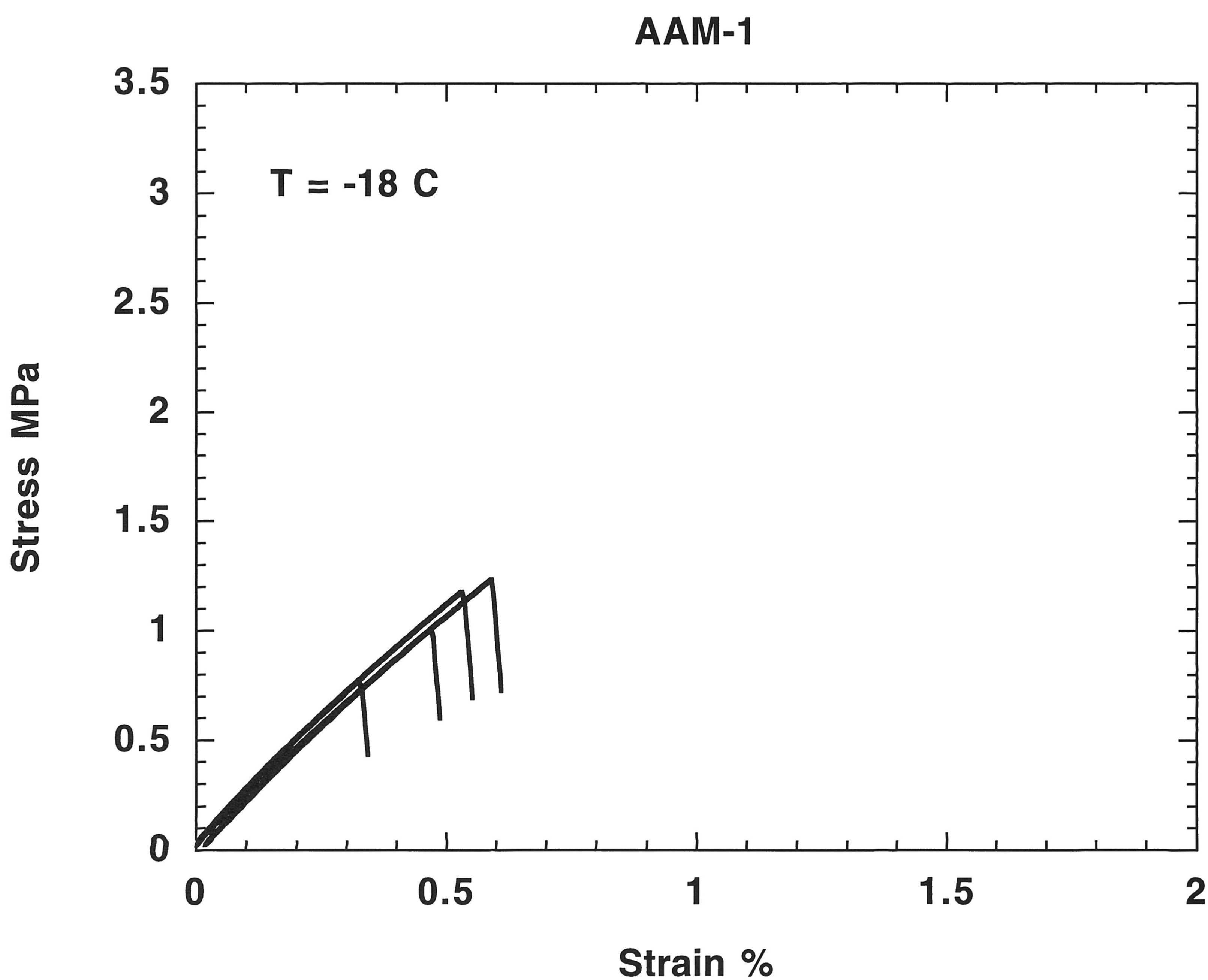


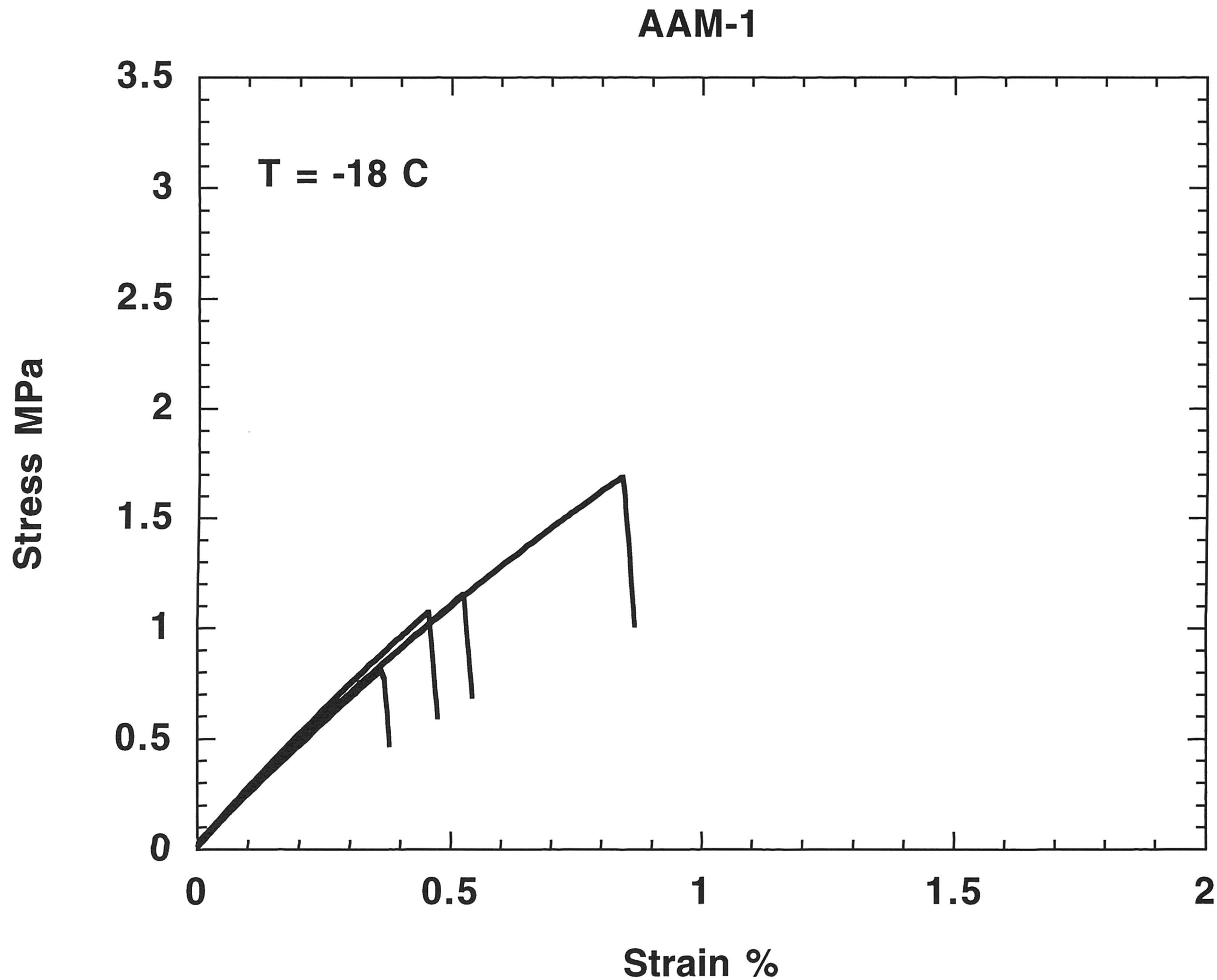

AAD-1
T = -18 C
Stress MPa
3.5
3
2.5
2
1.5
1
0.5
0
0
0.5
1
1.5
2
Strain %


AAG-1
T = -18 C
3.5
3
2.5
2
1.5
1
0.5
0
Stress MPa
0
0.5
1
1.5
2
Strain %

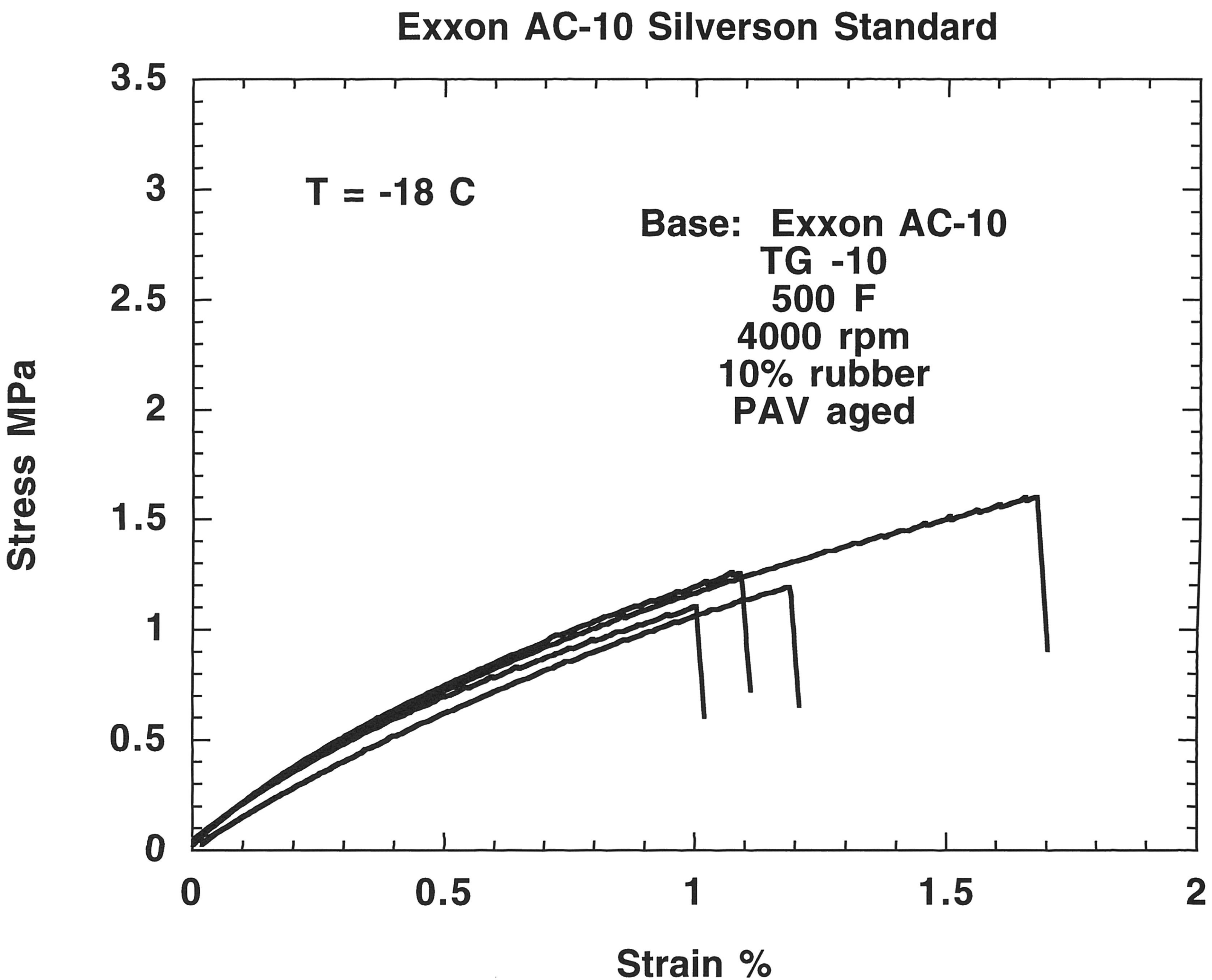

AAG-1 Reused
T = -18 C
Stress MPa
0
0.5
1
1.5
2
2.5
3
3.5
Strain %
0
0.5
1
1.5
2

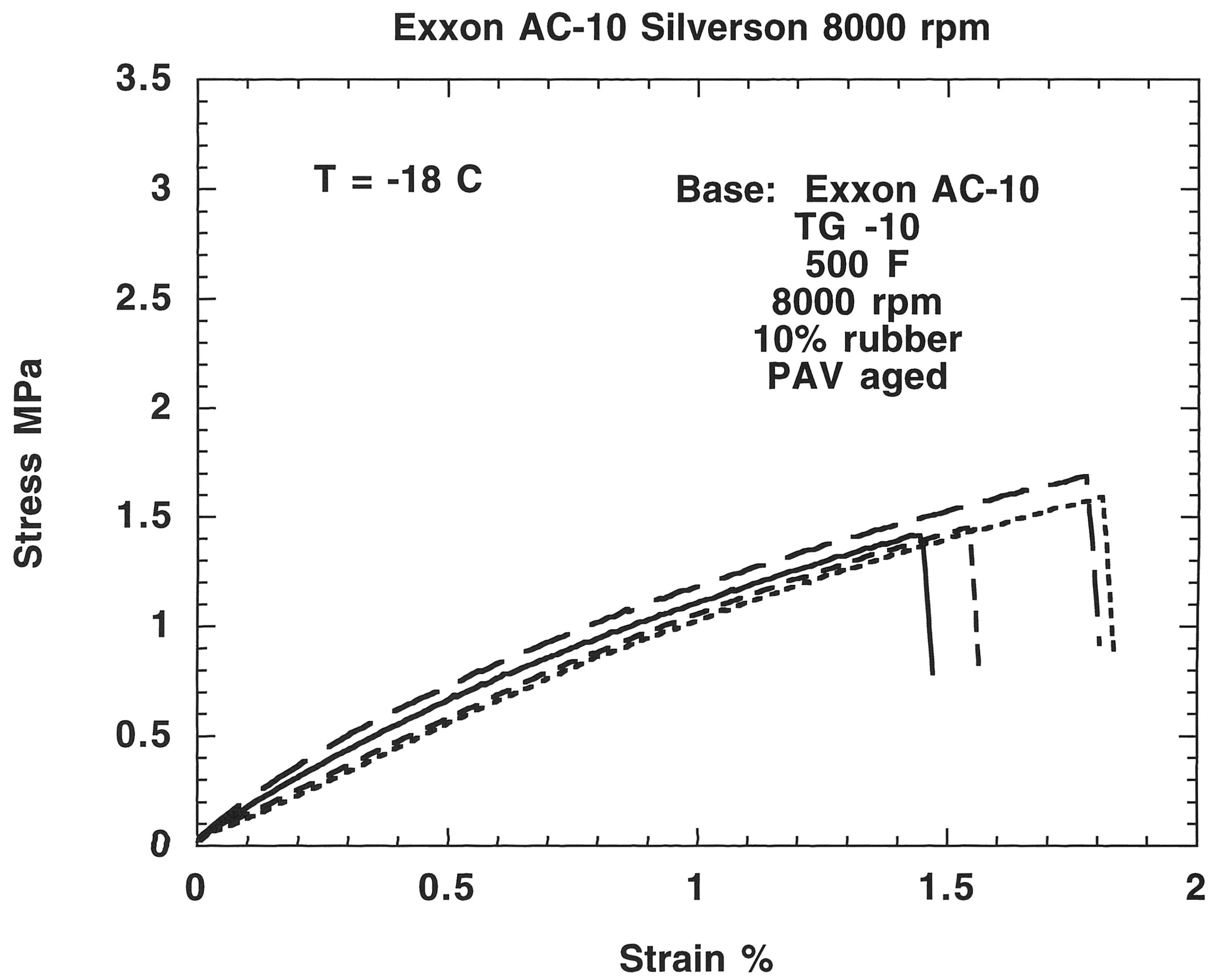

AAF-1
T = -18 C
Stress MPa
3.5
3
2.5
2
1.5
1
0.5
0
0
0.5
1
1.5
2
Strain %

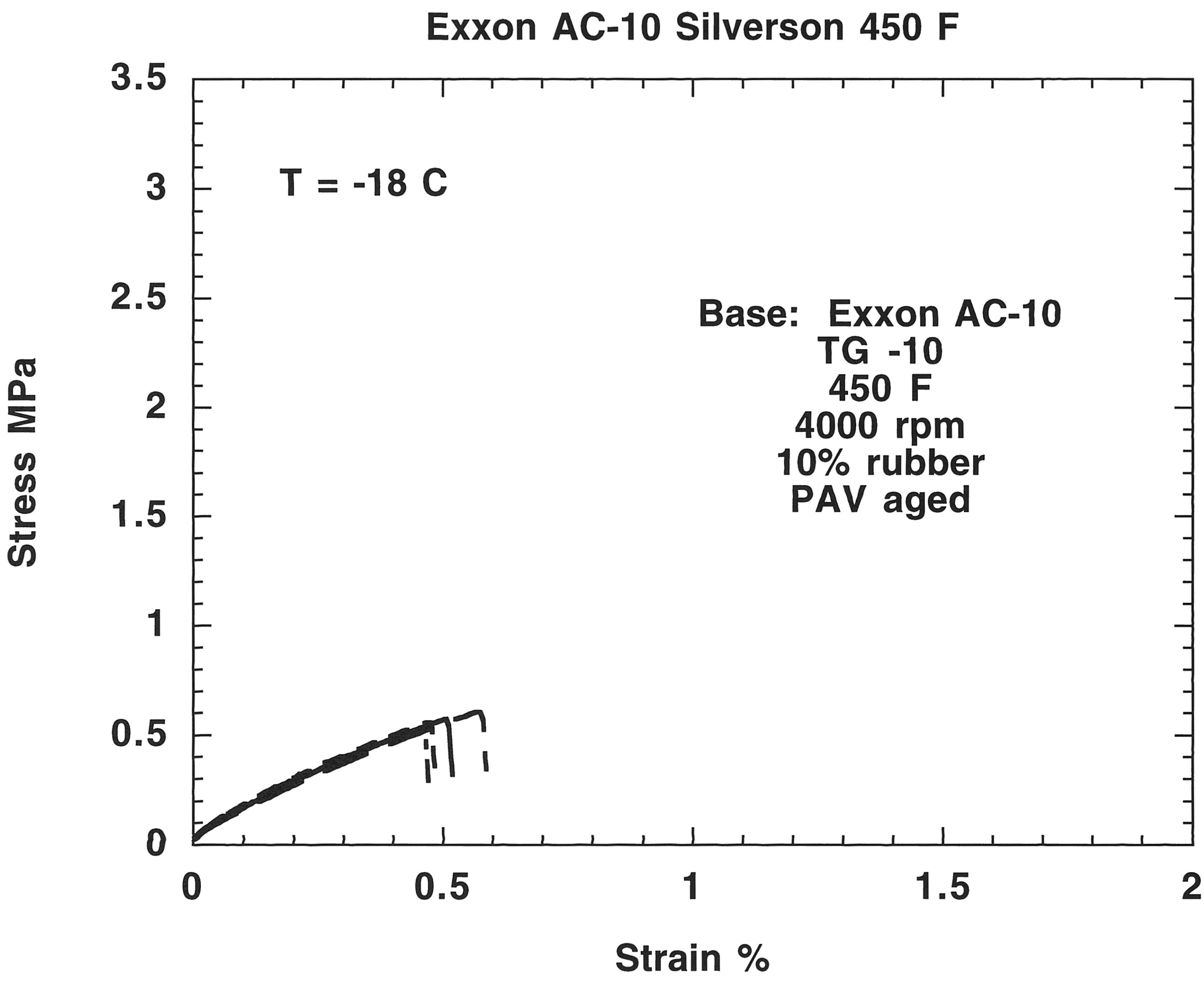

AAM-1
T = -18 C
Stress MPa
3.5
3
2.5
2
1.5
1
0.5
0
0
0.5
1
1.5
2
Strain %

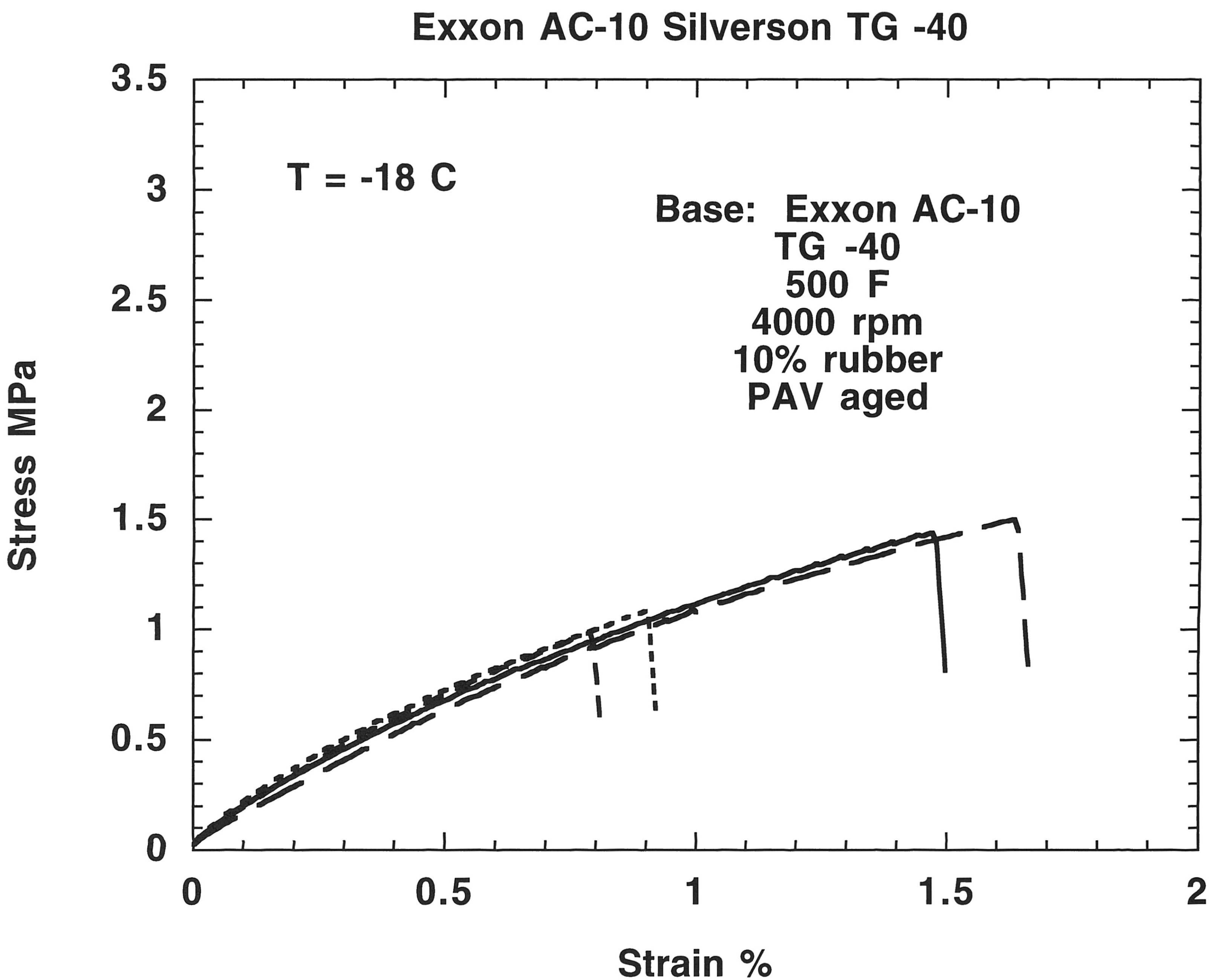

AAM-1
T = -18 C
Stress MPa
Strain %
3.5
3
2.5
2
1.5
1
0.5
0
0
0.5
1
1.5
2

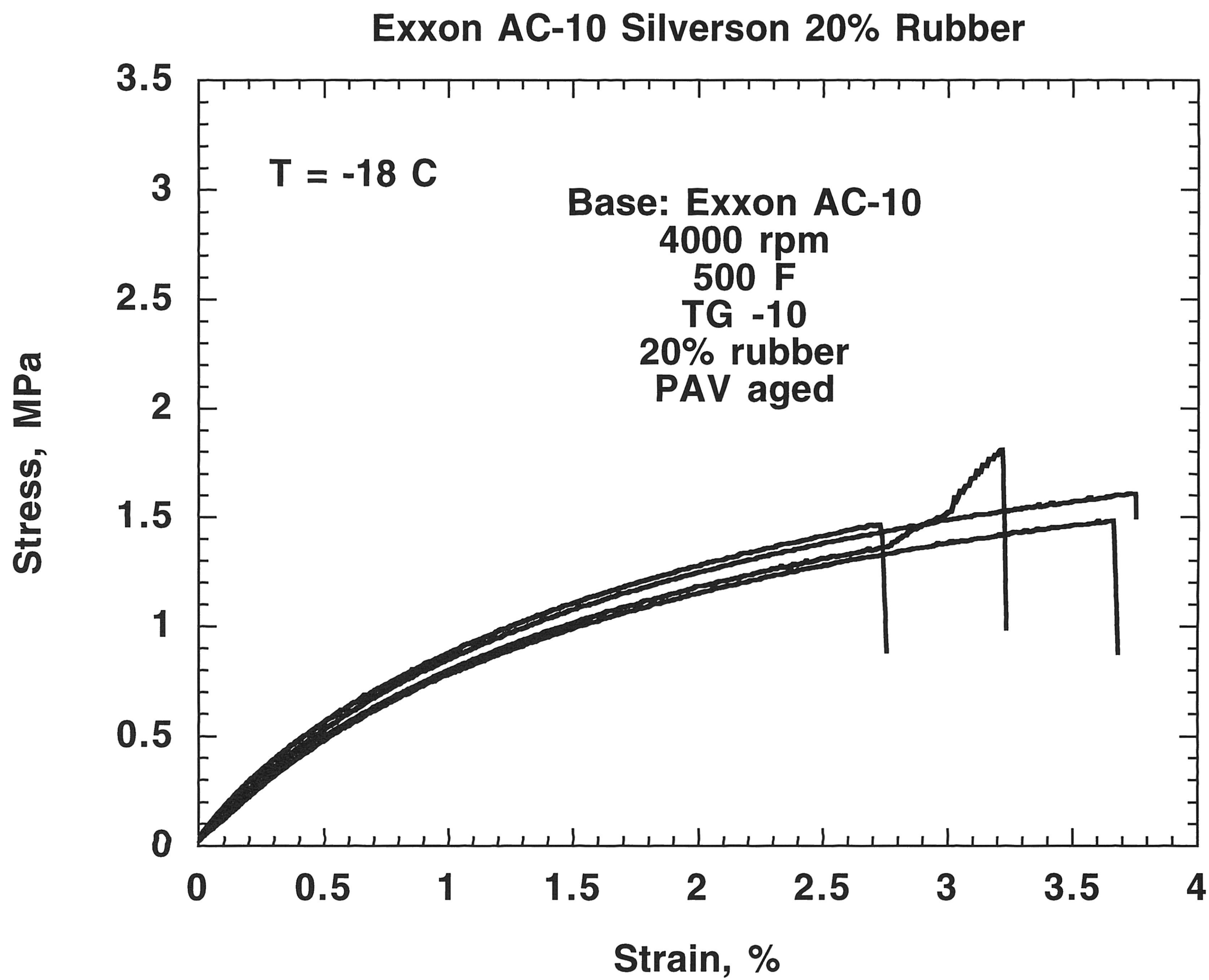
Appendix E: Exxon Silverson Stress-Strain Curves

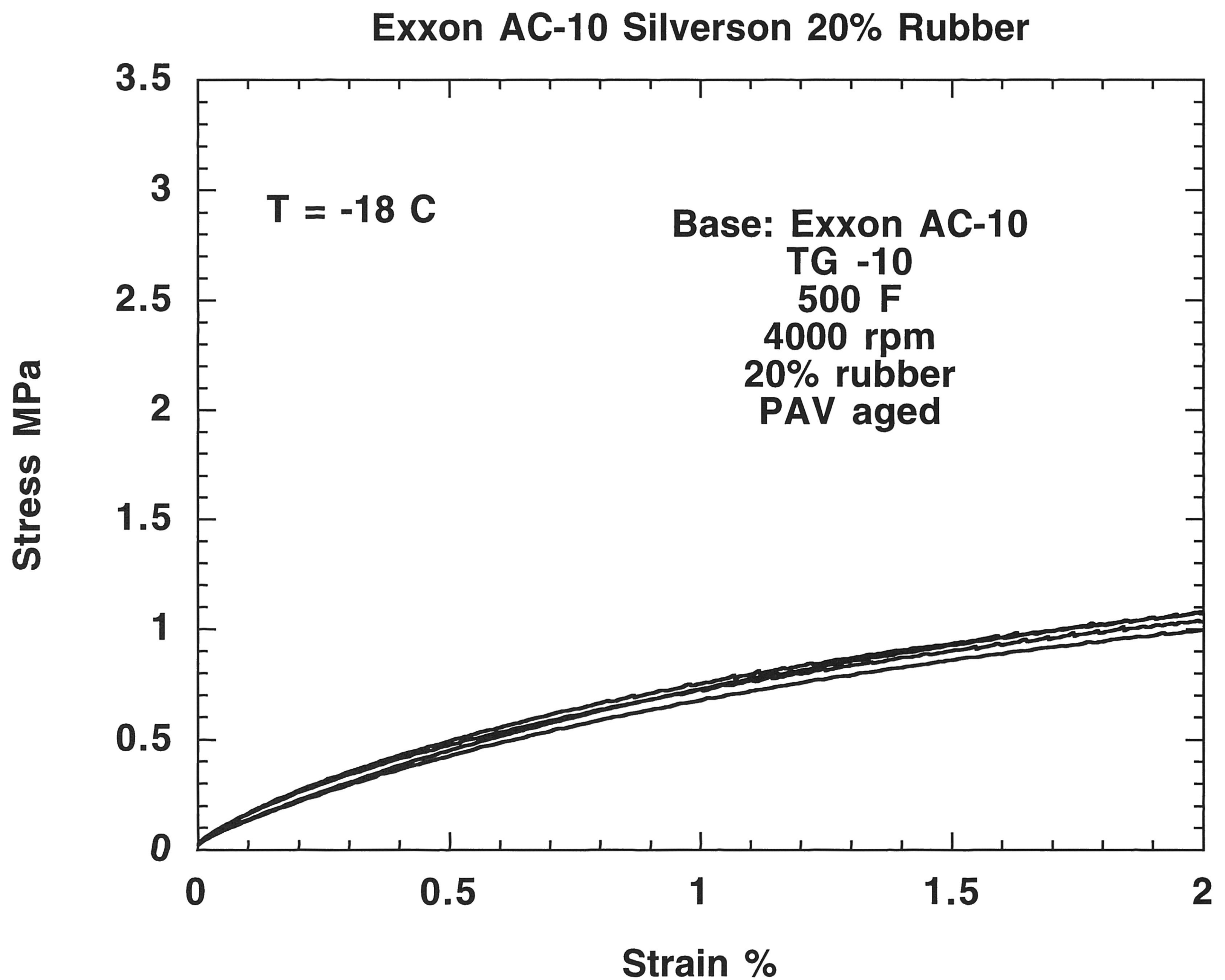

Exxon AC-10 Silverson Standard
T = -18 C
Base: Exxon AC-10
TG -10
500 F
4000 rpm
10% rubber
PAV aged
Stress MPa
0
0.5
1
1.5
2
2.5
3
3.5
Strain %
0
0.5
1
1.5
2

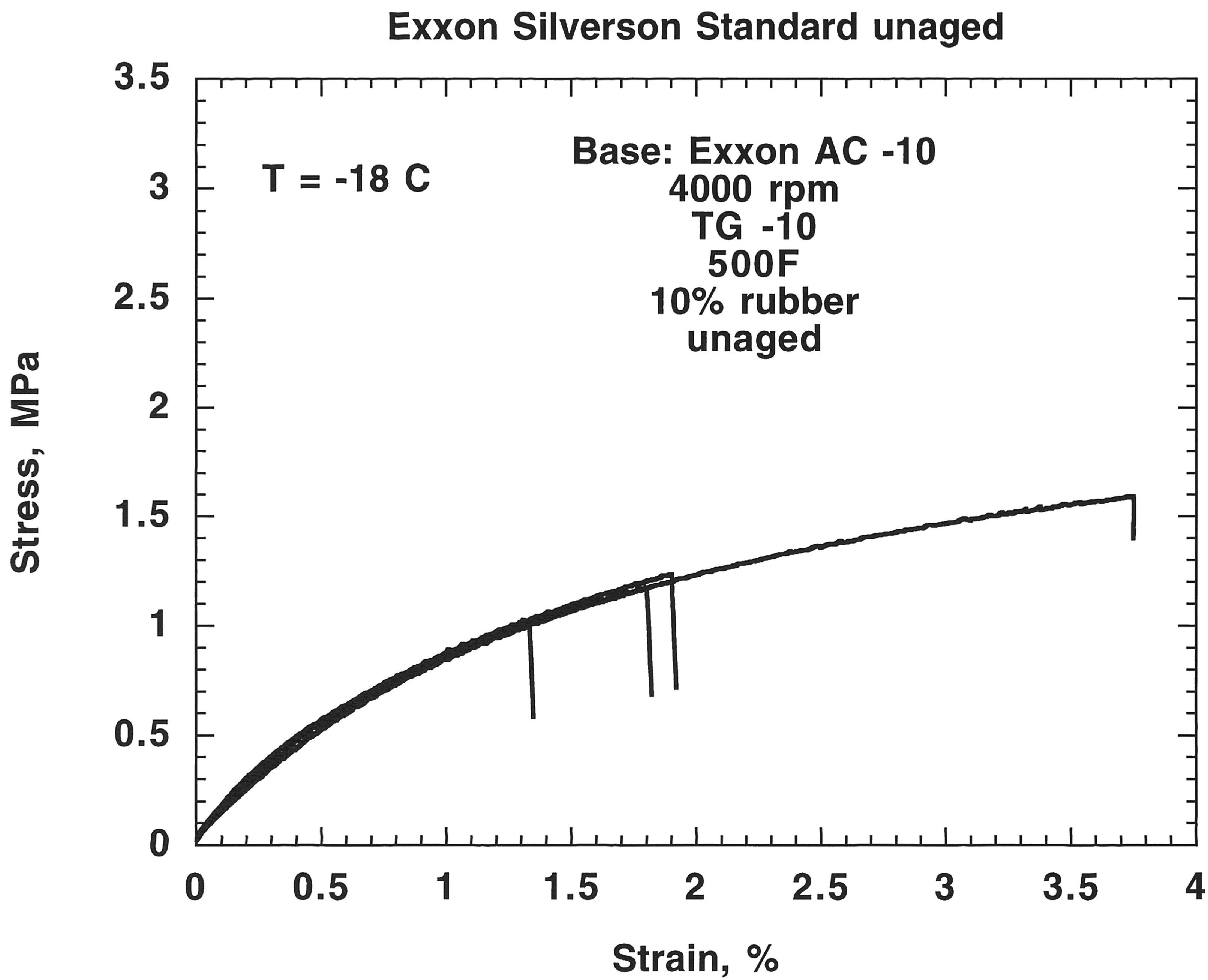

Exxon AC-10 Silverson 8000 rpm
T = -18 C
Base: Exxon AC-10
TG -10
500 F
8000 rpm
10% rubber
PAV aged
Stress MPa
Strain %
0
0.5
1
1.5
2
2.5
3
3.5
0
0.5
1
1.5
2


Exxon AC-10 Silverson 450 F
T = -18 C
Base: Exxon AC-10
TG -10
450 F
4000 rpm
10% rubber
PAV aged
Stress MPa
Strain %
0
0.5
1
1.5
2
2.5
3
3.5
0
0.5
1
1.5
2

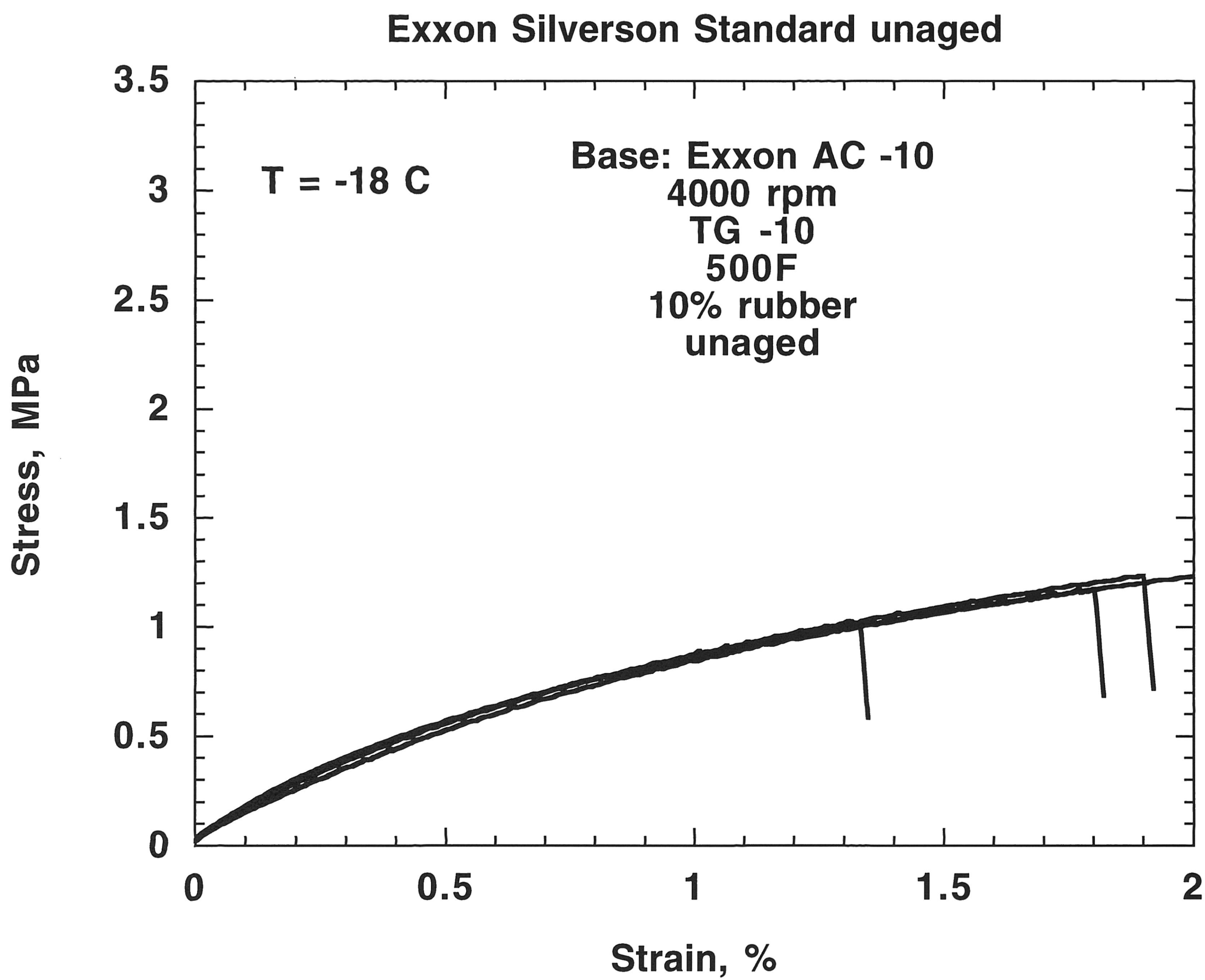

Exxon AC-10 Silverson TG -40
T = -18 C
Base: Exxon AC-10
TG -40
500 F
4000 rpm
10% rubber
PAV aged
Stress MPa
Strain %
0
0.5
1
1.5
2
2.5
3
3.5
0
0.5
1
1.5
2


Exxon AC-10 Silverson 20% Rubber
T = -18 C
Base: Exxon AC-10
4000 rpm
500 F
TG -10
20% rubber
PAV aged
Stress, MPa
Strain, %
0
0.5
1
1.5
2
2.5
3
3.5
4

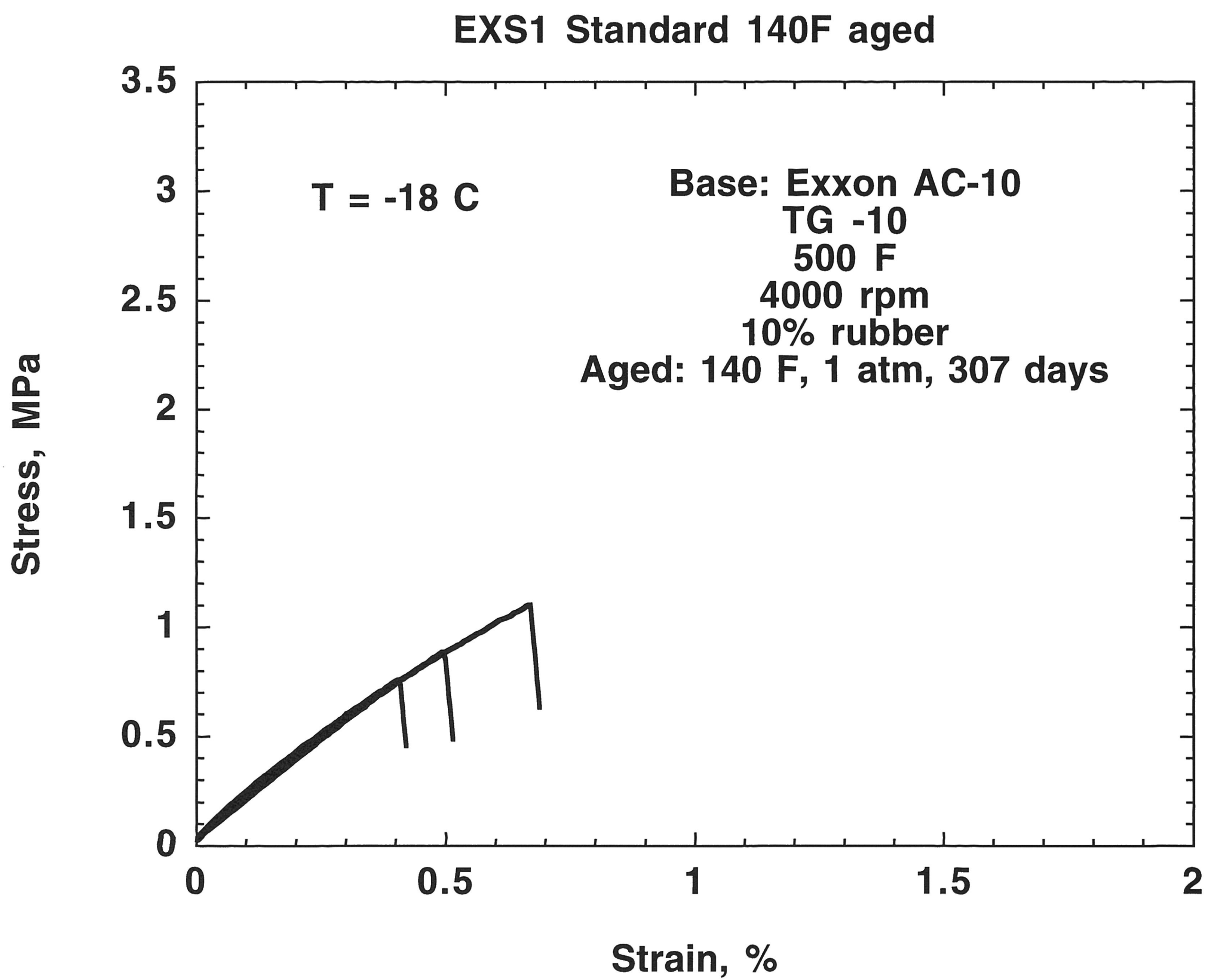

Exxon AC-10 Silverson 20% Rubber
T = -18 C
Base: Exxon AC-10
TG -10
500 F
4000 rpm
20% rubber
PAV aged
Stress MPa
Strain %
0
0.5
1
1.5
2
2.5
3
3.5
0
0.5
1
1.5
2

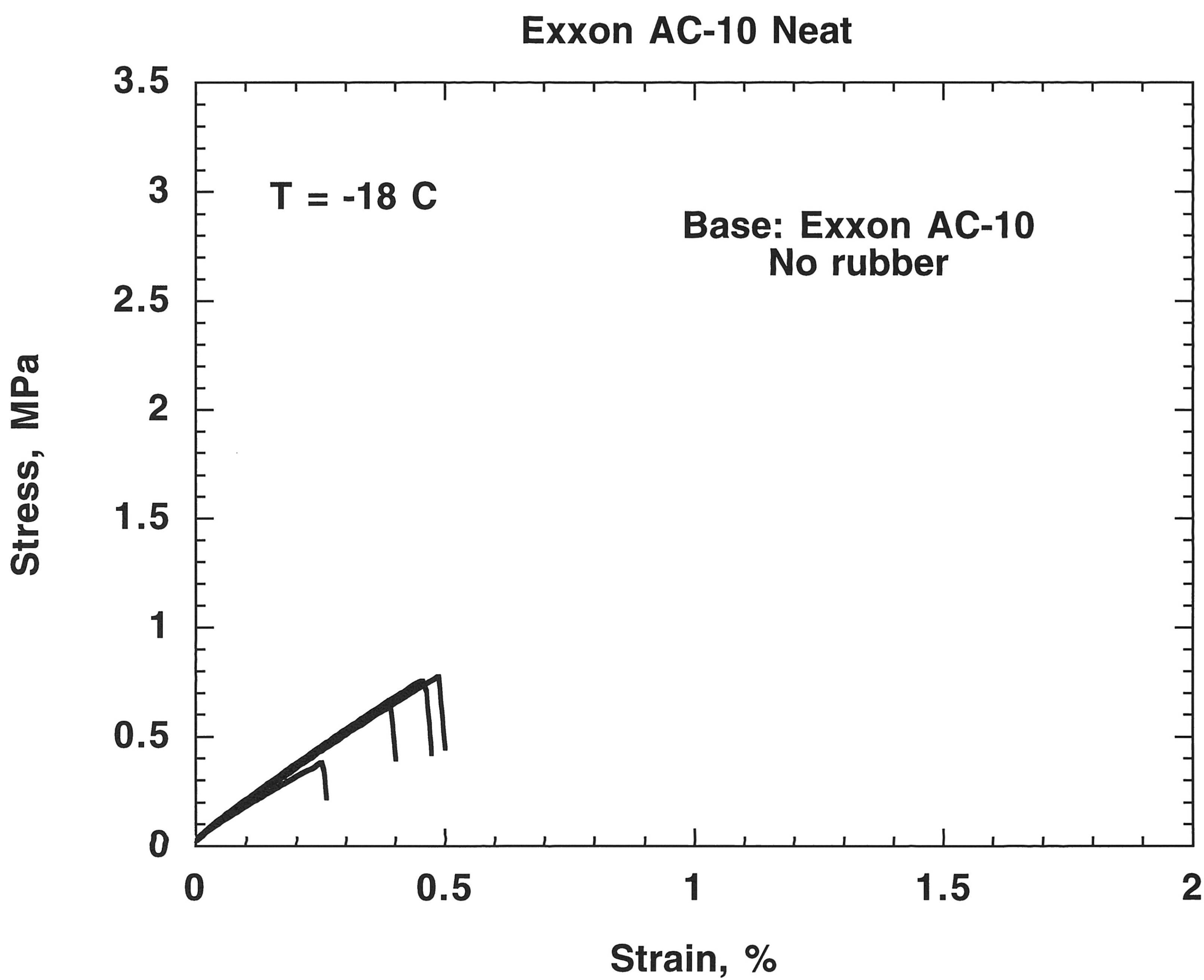


Exxon Silverson Standard unaged
T = -18 C
Base: Exxon AC -10
4000 rpm
TG -10
500F
10% rubber
unaged
Stress, MPa
0
0.5
1
1.5
2
2.5
3
3.5
Strain, %
0
0.5
1
1.5
2
2.5
3
3.5
4

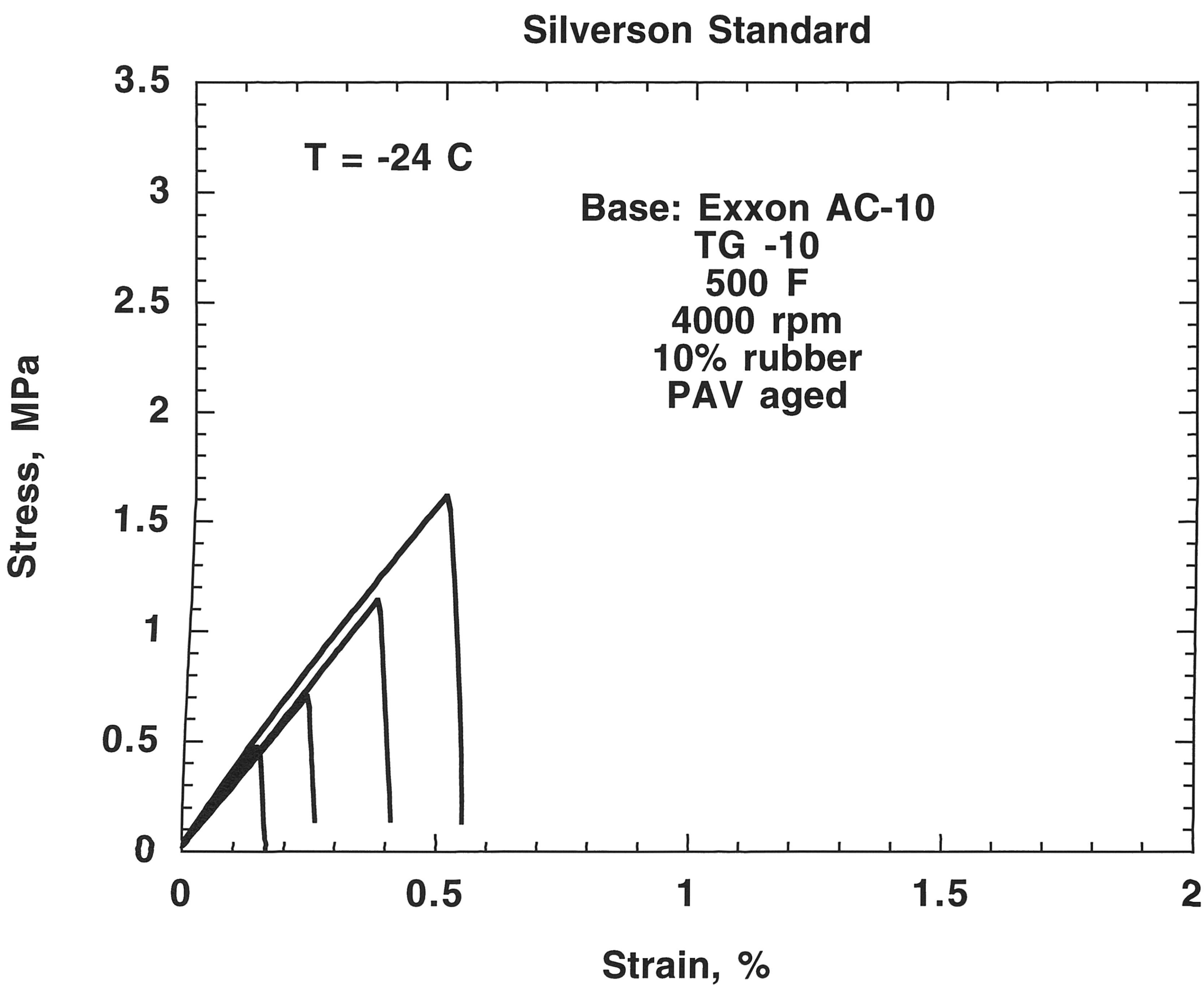


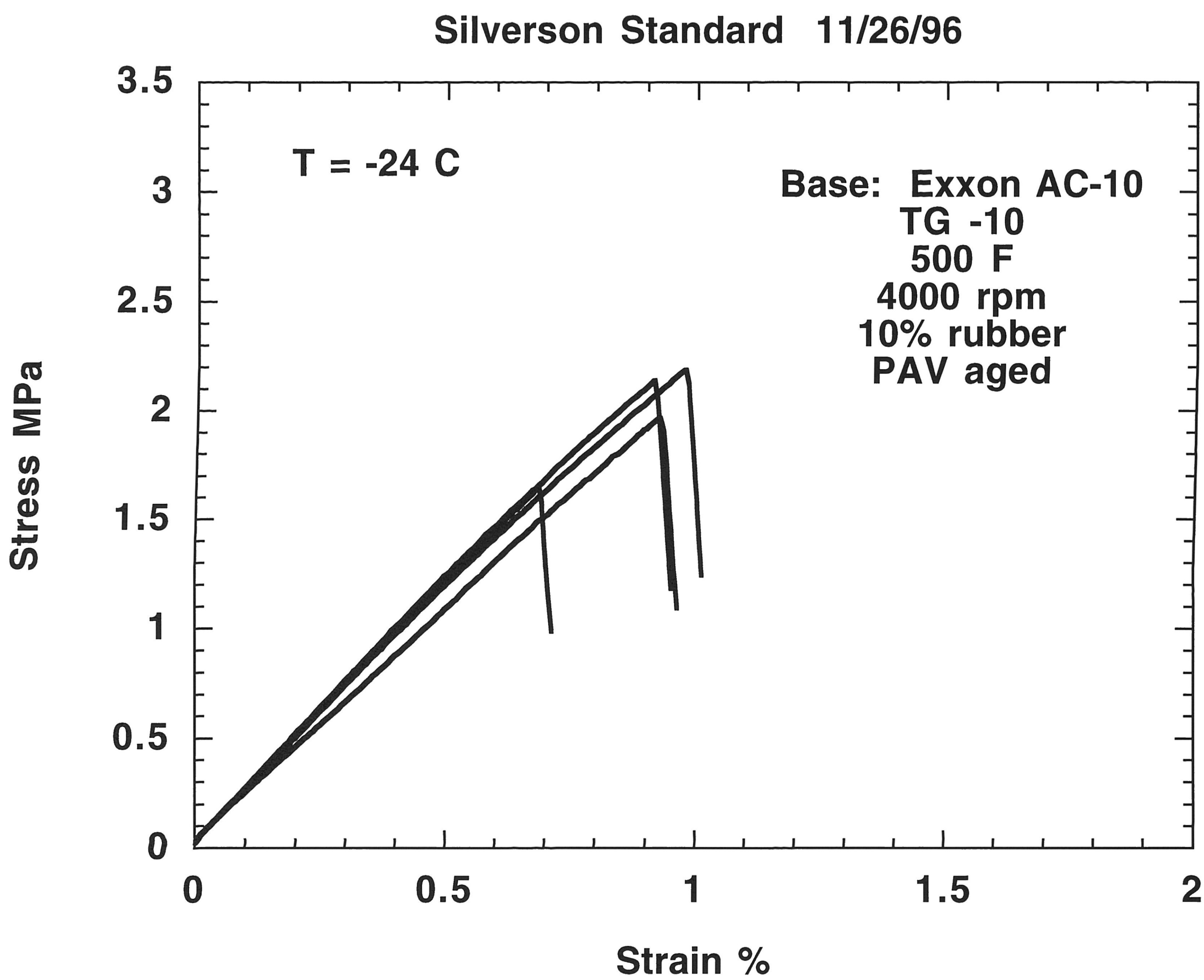
Exxon Silverson Standard unaged
T = -18 C
Base: Exxon AC -10
4000 rpm
TG -10
500F
10% rubber
unaged
Stress, MPa
0
0.5
1
1.5
2
2.5
3
3.5
Strain, %
0
0.5
1
1.5
2

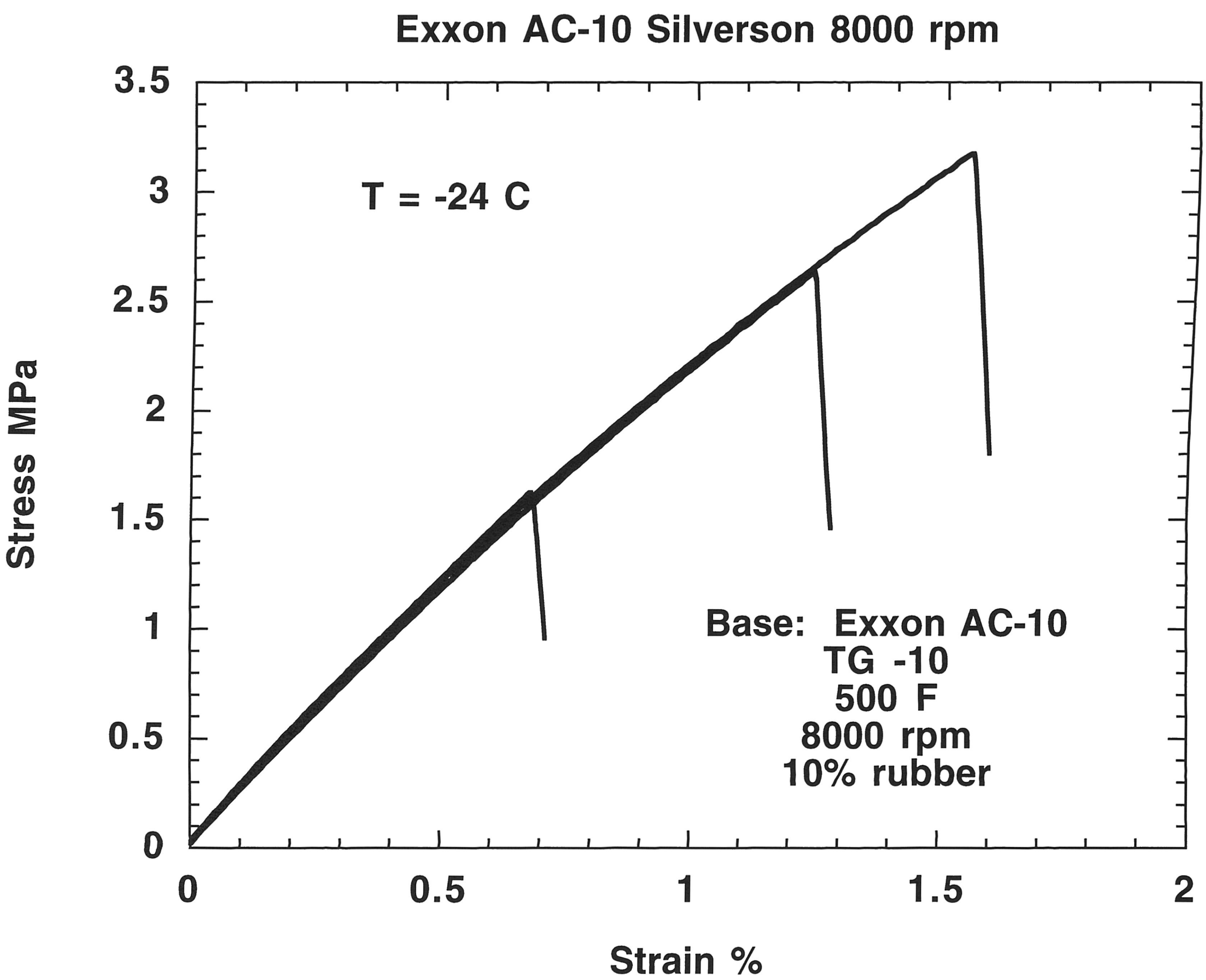

EXS1 Standard 140F aged
T = -18 C
Base: Exxon AC-10
TG -10
500 F
4000 rpm
10% rubber
Aged: 140 F, 1 atm, 307 days
Stress, MPa
Strain, %
0
0.5
1
1.5
2
2.5
3
3.5
0
0.5
1
1.5
2

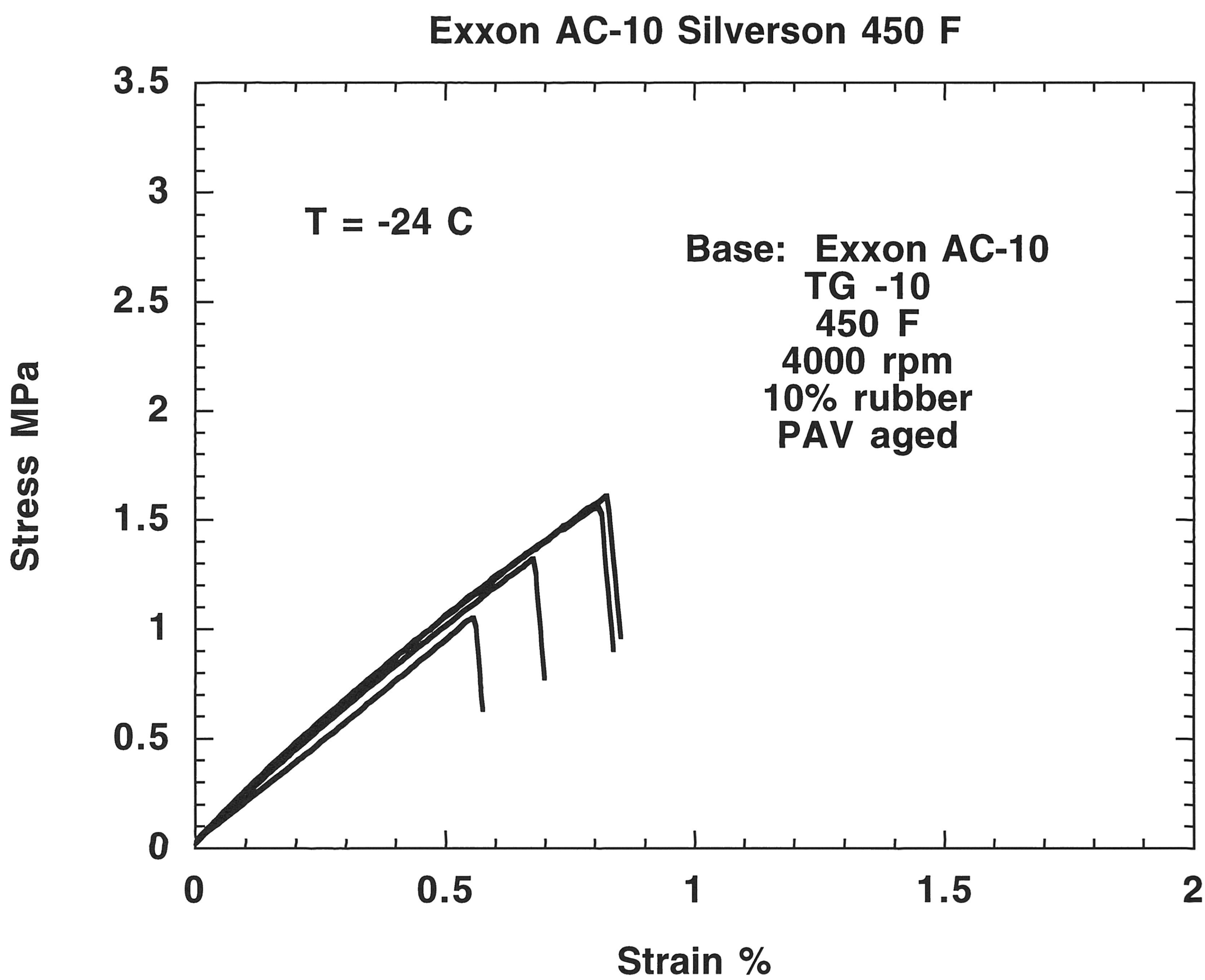


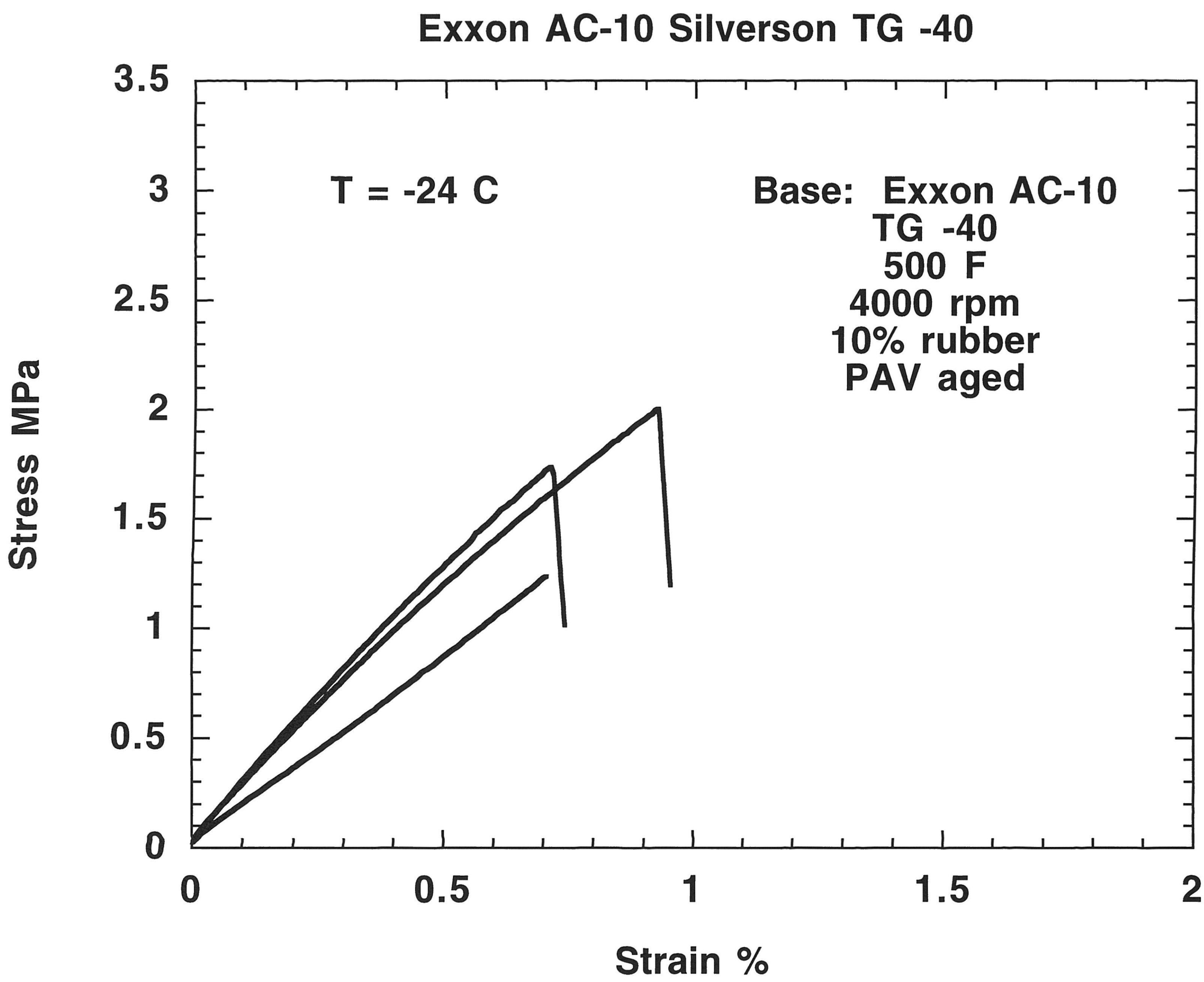
Exxon AC-10 Neat
T = -18 C
Base: Exxon AC-10
No rubber
Stress, MPa
0
0.5
1
1.5
2
2.5
3
3.5
Strain, %
0
0.5
1
1.5
2


Silverson Standard
T = -24 C
Base: Exxon AC-10
TG -10
500 F
4000 rpm
10% rubber
PAV aged
Stress, MPa
0
0.5
1
1.5
2
2.5
3
3.5
Strain, %
0
0.5
1
1.5
2

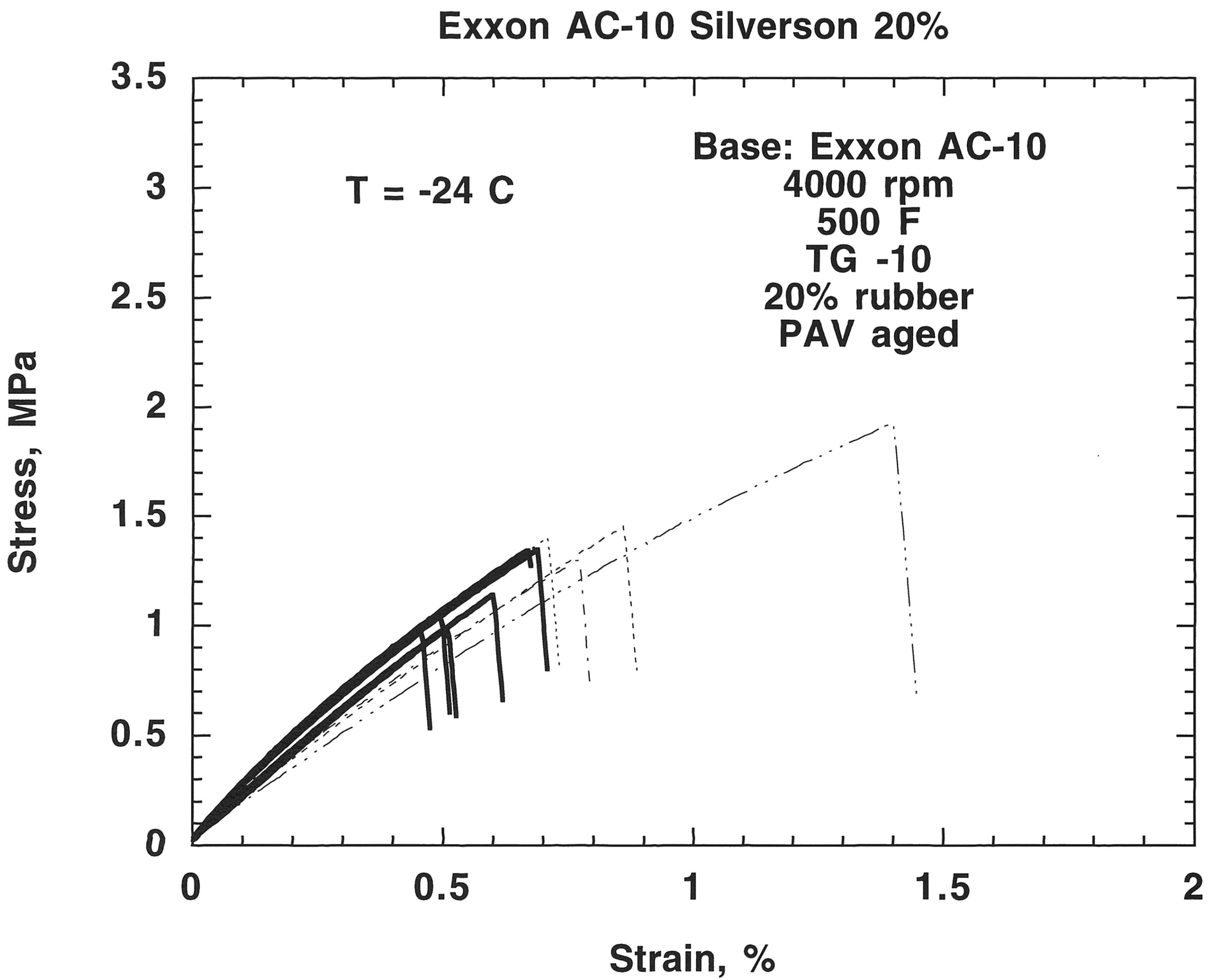

Silverson Standard 11/26/96
T = -24 C
Base: Exxon AC-10
TG -10
500 F
4000 rpm
10% rubber
PAV aged
Stress MPa
Strain %
0
0.5
1
1.5
2
2.5
3
3.5
0
0.5
1
1.5
2


Exxon AC-10 Silverson 8000 rpm
Stress MPa
3.5
3
2.5
2
1.5
1
0.5
0
T = -24 C
Base: Exxon AC-10
TG -10
500 F
8000 rpm
10% rubber
0
0.5
1
1.5
2
Strain %

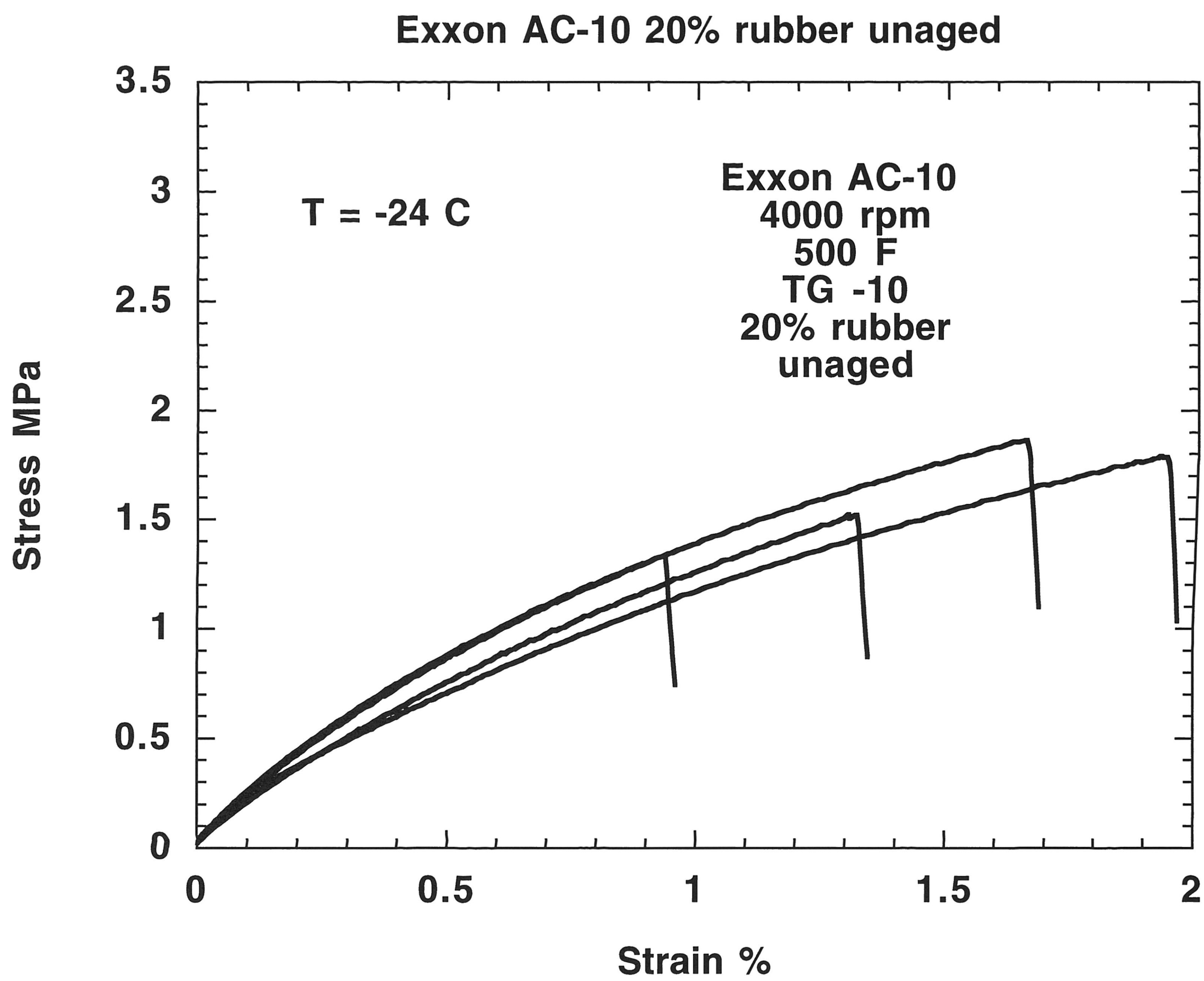

Exxon AC-10 Silverson 450 F
T = -24 C
Base: Exxon AC-10
TG -10
450 F
4000 rpm
10% rubber
PAV aged
Stress MPa
3.5
3
2.5
2
1.5
1
0.5
0
0
0.5
1
1.5
2
Strain %

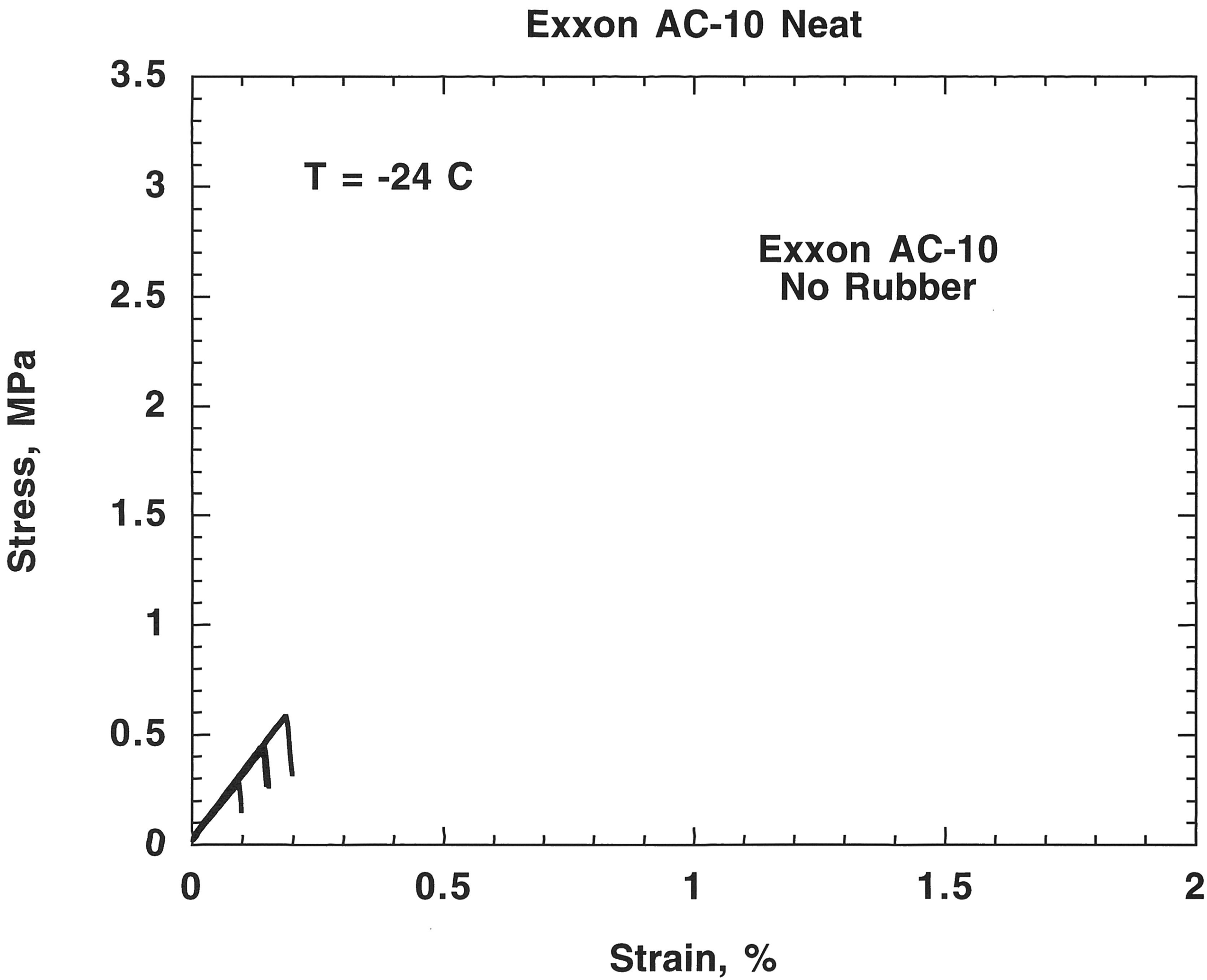


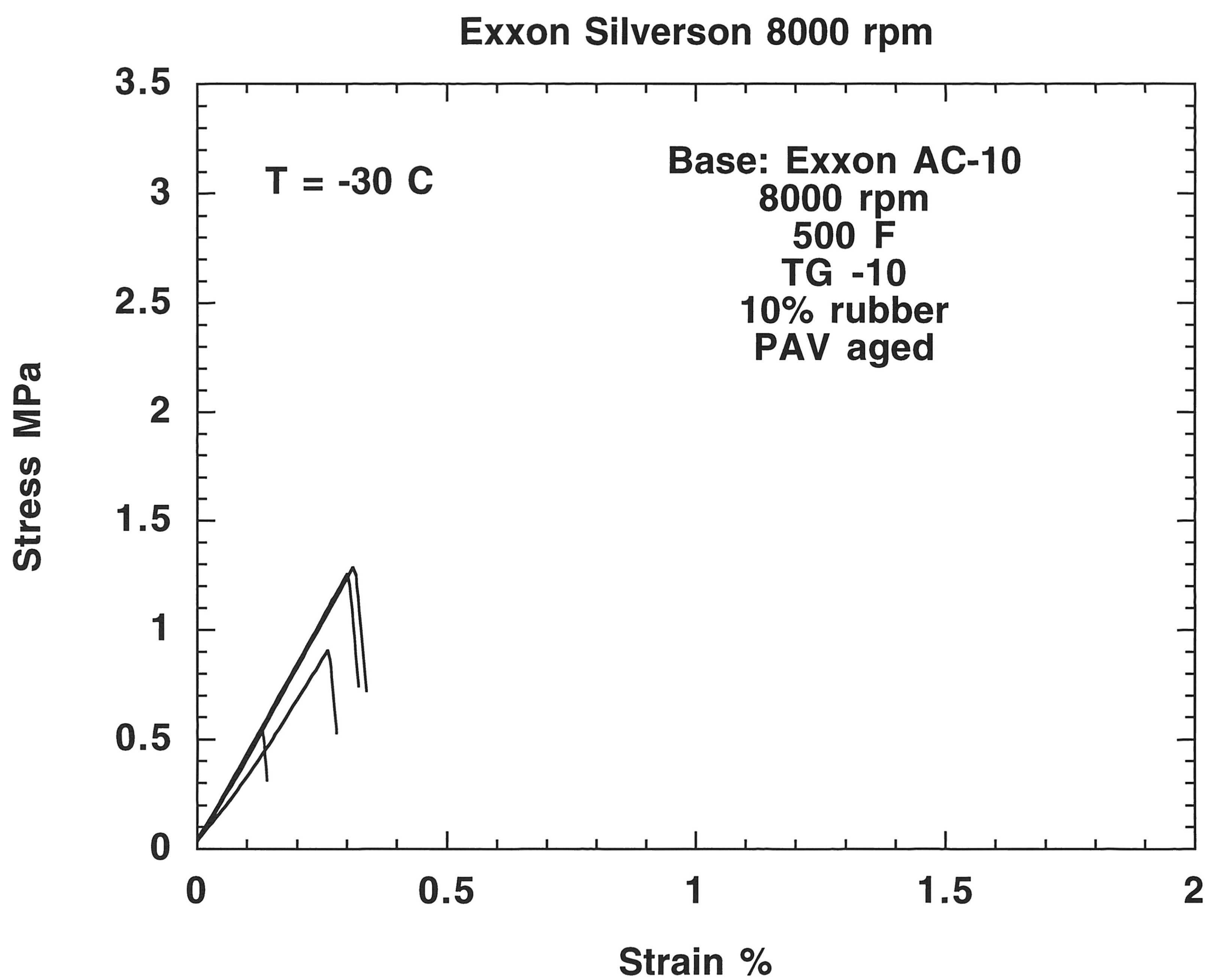
Exxon AC-10 Silverson TG -40
Stress MPa
3.5
3
2.5
2
1.5
1
0.5
0
T = -24 C
Base: Exxon AC-10
TG -40
500 F
4000 rpm
10% rubber
PAV aged
0
0.5
1
1.5
2
Strain %



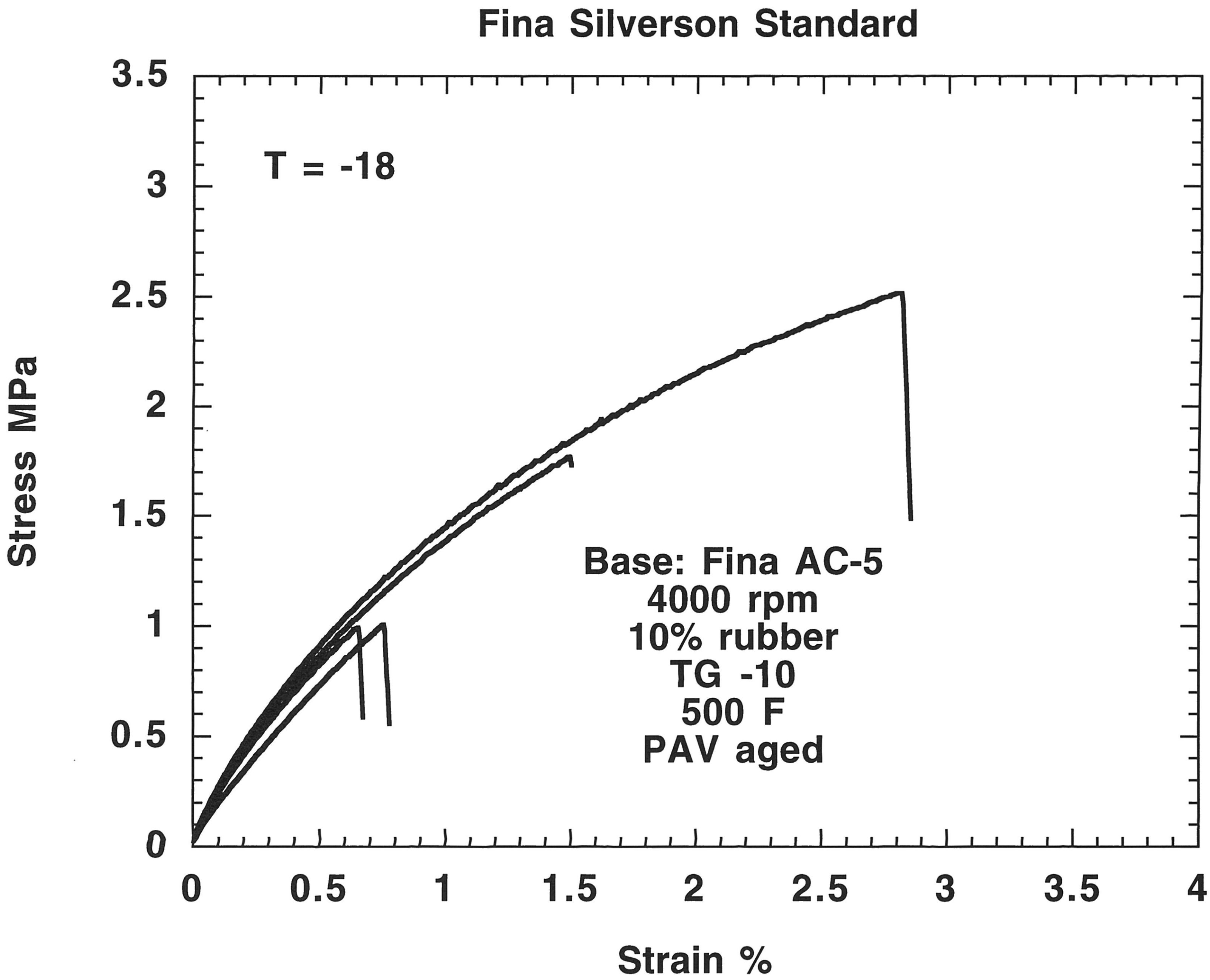
Exxon AC-10 Silverson 20%
Stress, MPa
3.5
3
2.5
2
1.5
1
0.5
0
T = -24 C
Base: Exxon AC-10
4000 rpm
500 F
TG -10
20% rubber
PAV aged
0
0.5
1
1.5
2
Strain, %

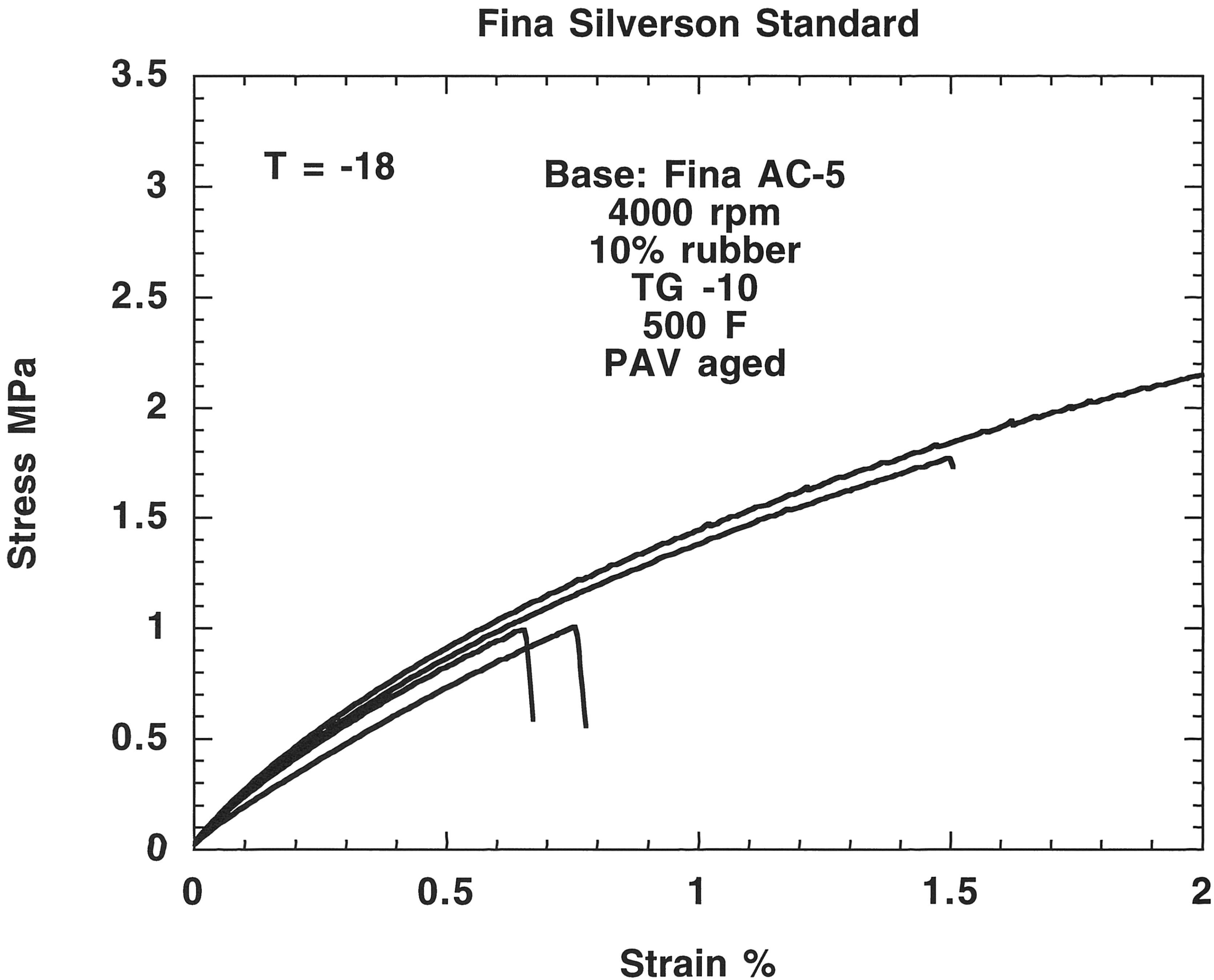

Exxon AC-10 20% rubber unaged
3.5
3
2.5
2
1.5
1
0.5
0
Stress MPa
T = -24 C
Exxon AC-10
4000 rpm
500 F
TG -10
20% rubber
unaged
0
0.5
1
1.5
2
Strain %

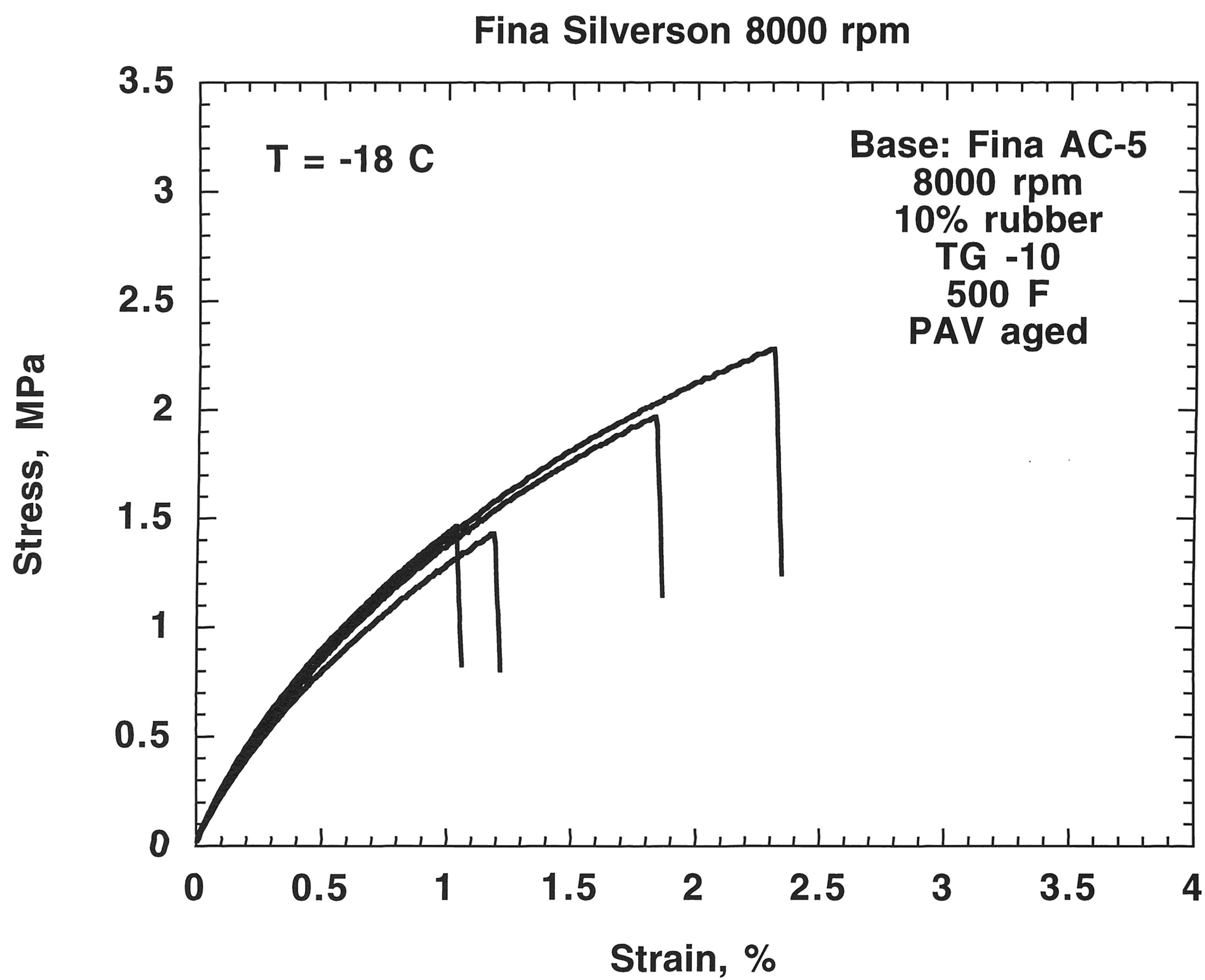

Exxon AC-10 Neat
T = -24 C
Exxon AC-10
No Rubber
Stress, MPa
3.5
3
2.5
2
1.5
1
0.5
0
0
0.5
1
1.5
2
Strain, %

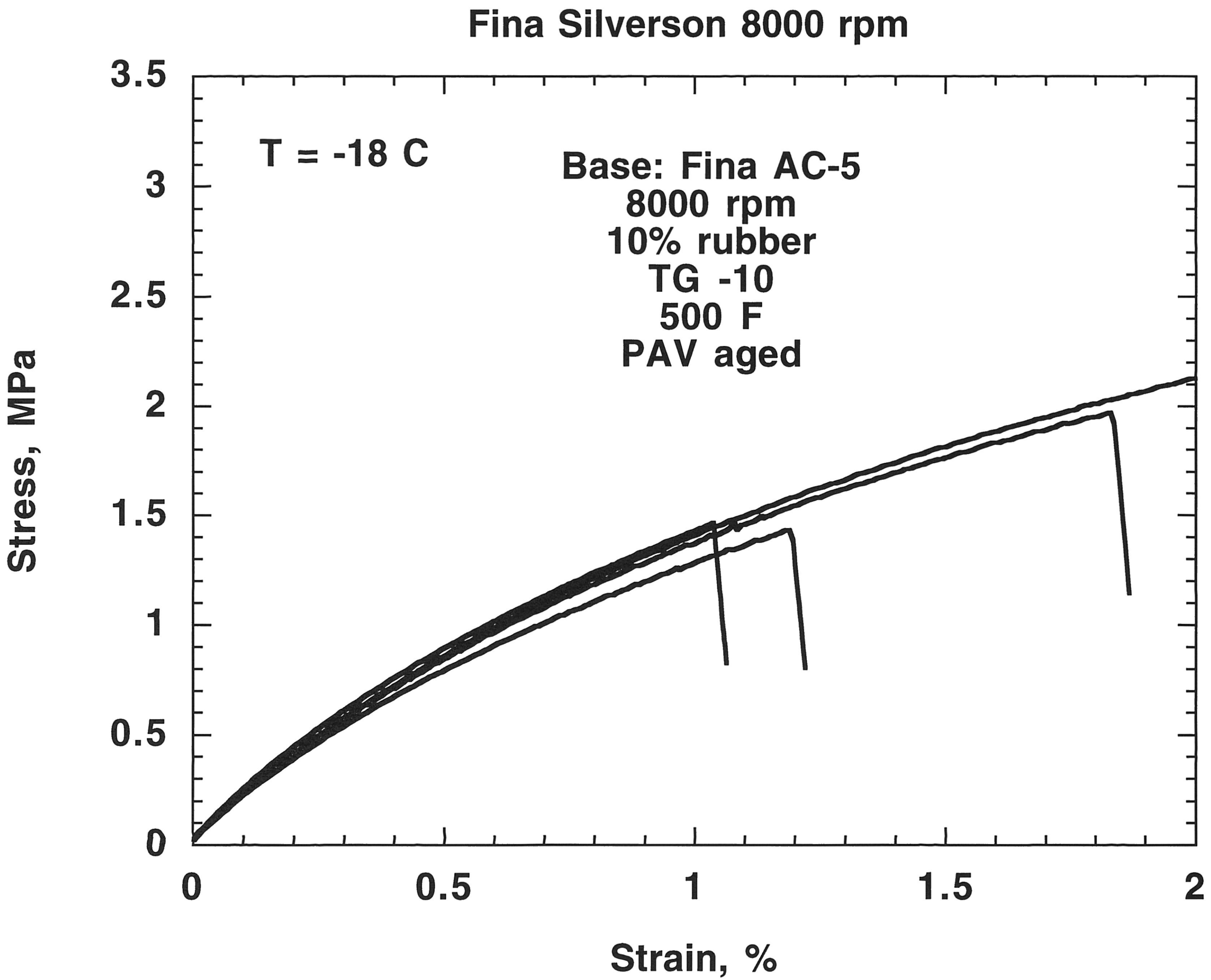

Exxon Silverson 8000 rpm
T = -30 C
Base: Exxon AC-10
8000 rpm
500 F
TG -10
10% rubber
PAV aged
Stress MPa
Strain %
0
0.5
1
1.5
2
2.5
3
3.5
0
0.5
1
1.5
2

Appendix F: Fina AC-5 Silverson Stress-Strain Curves

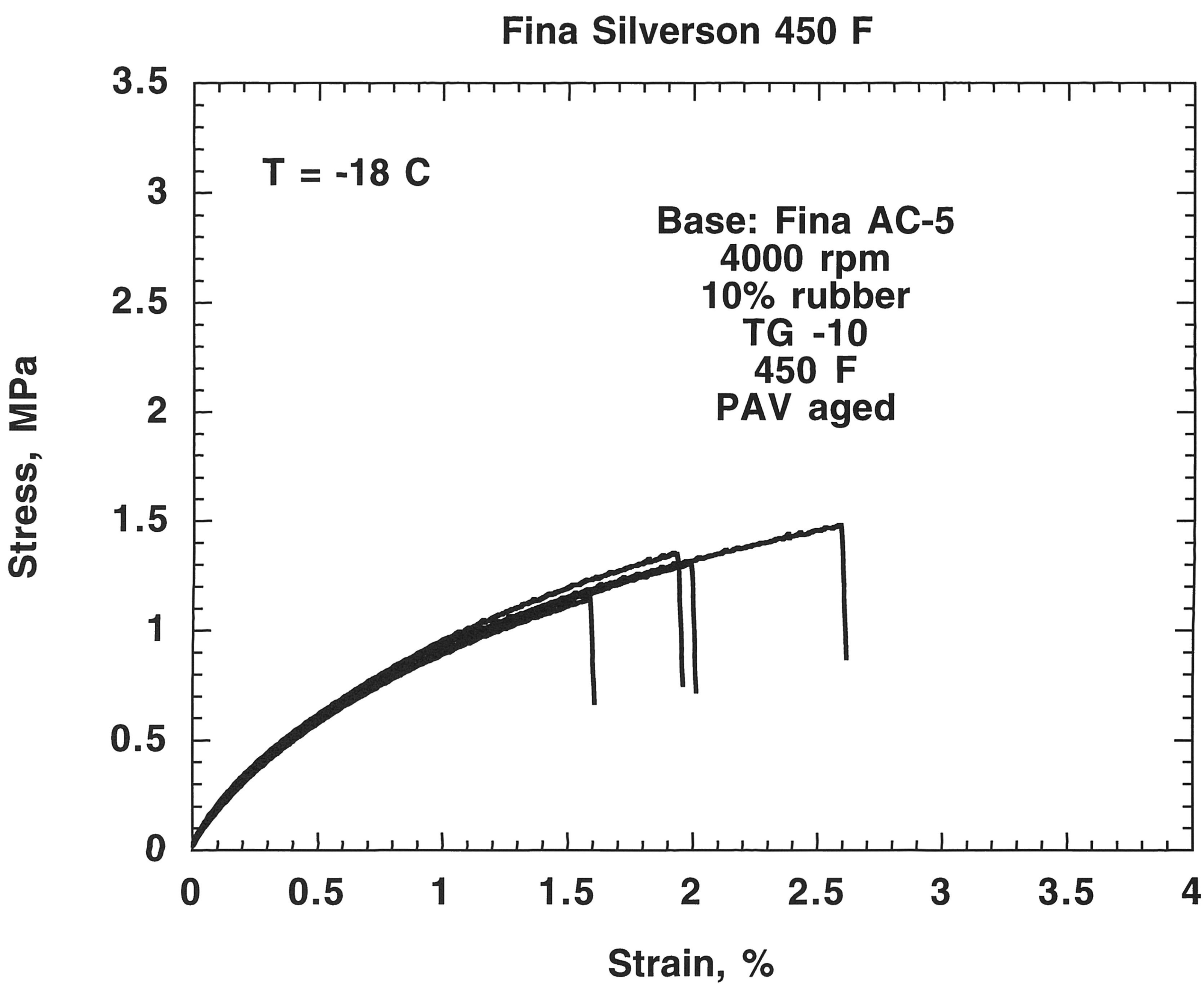

Fina Silverson Standard
T = -18
Base: Fina AC-5
4000 rpm
10% rubber
TG -10
500 F
PAV aged
Stress MPa
Strain %
0
0.5
1
1.5
2
2.5
3
3.5
4


Fina Silverson Standard
T = -18
Base: Fina AC-5
4000 rpm
10% rubber
TG -10
500 F
PAV aged
Stress MPa
Strain %
0
0.5
1
1.5
2
2.5
3
3.5

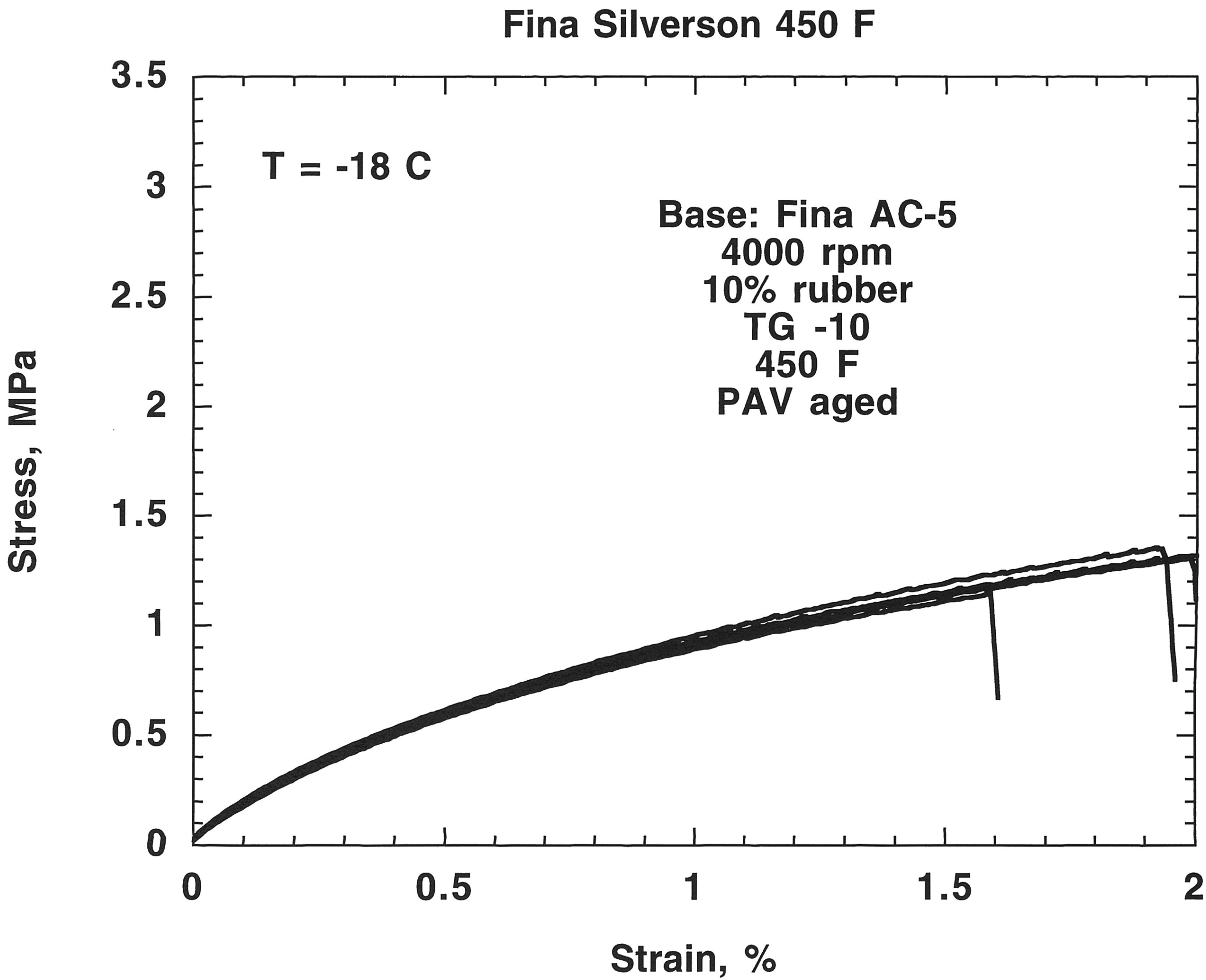

Fina Silverson 8000 rpm
T = -18 C
Base: Fina AC-5
8000 rpm
10% rubber
TG -10
500 F
PAV aged
Stress, MPa
Strain, %
0
0.5
1
1.5
2
2.5
3
3.5
4

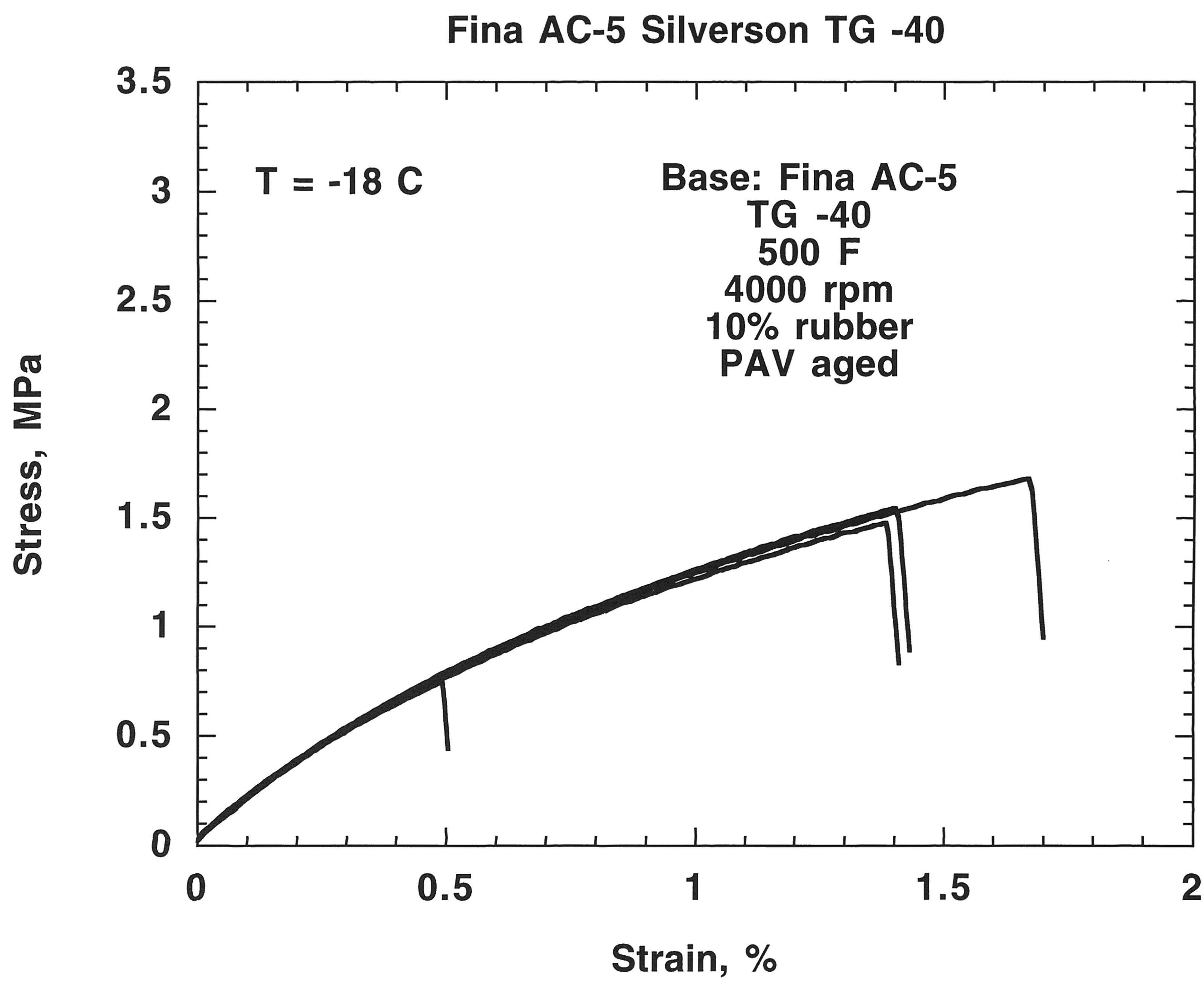


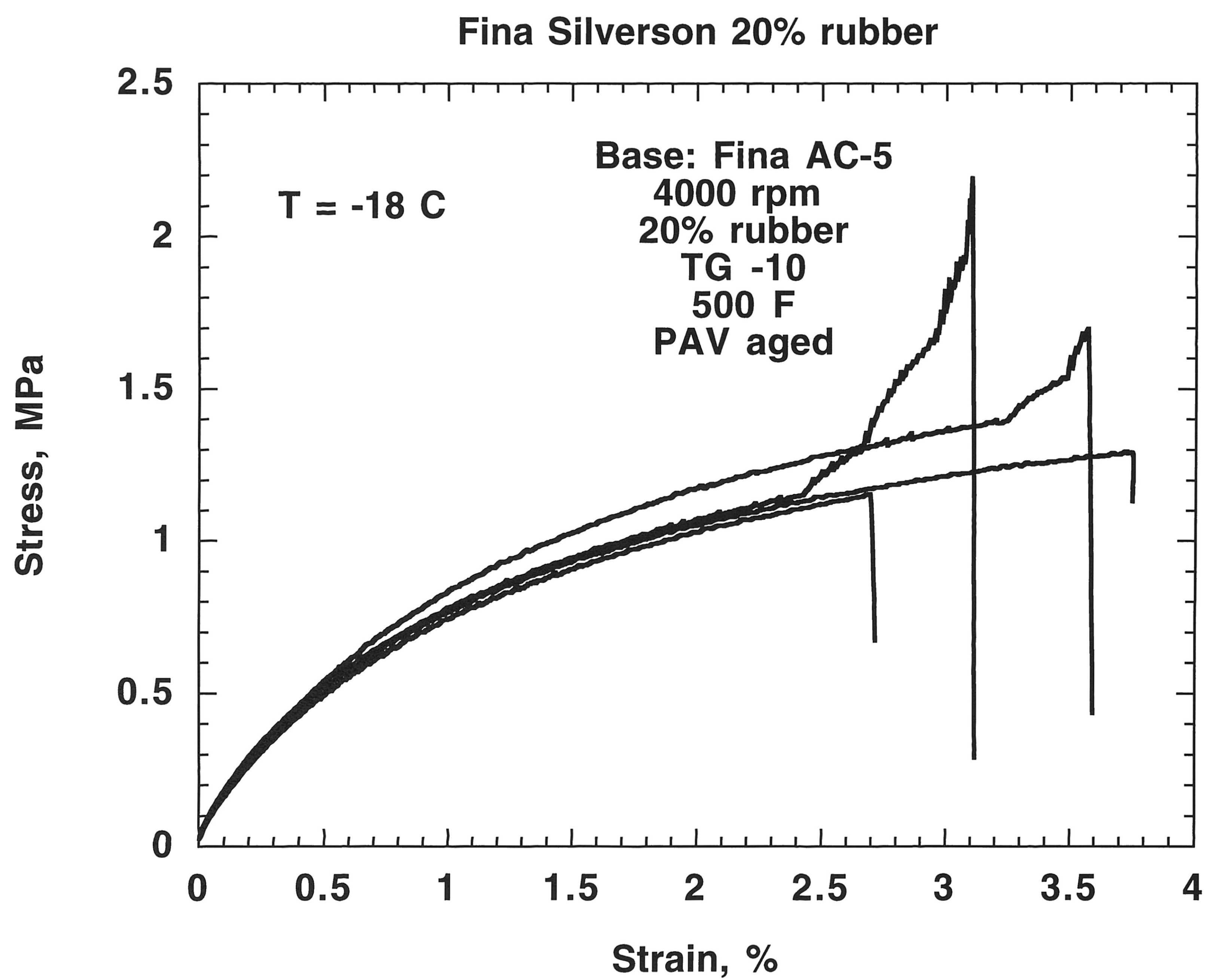
Fina Silverson 8000 rpm
T = -18 C
Base: Fina AC-5
8000 rpm
10% rubber
TG -10
500 F
PAV aged
Stress, MPa
Strain, %
0
0.5
1
1.5
2
2.5
3
3.5
0
0.5
1
1.5
2

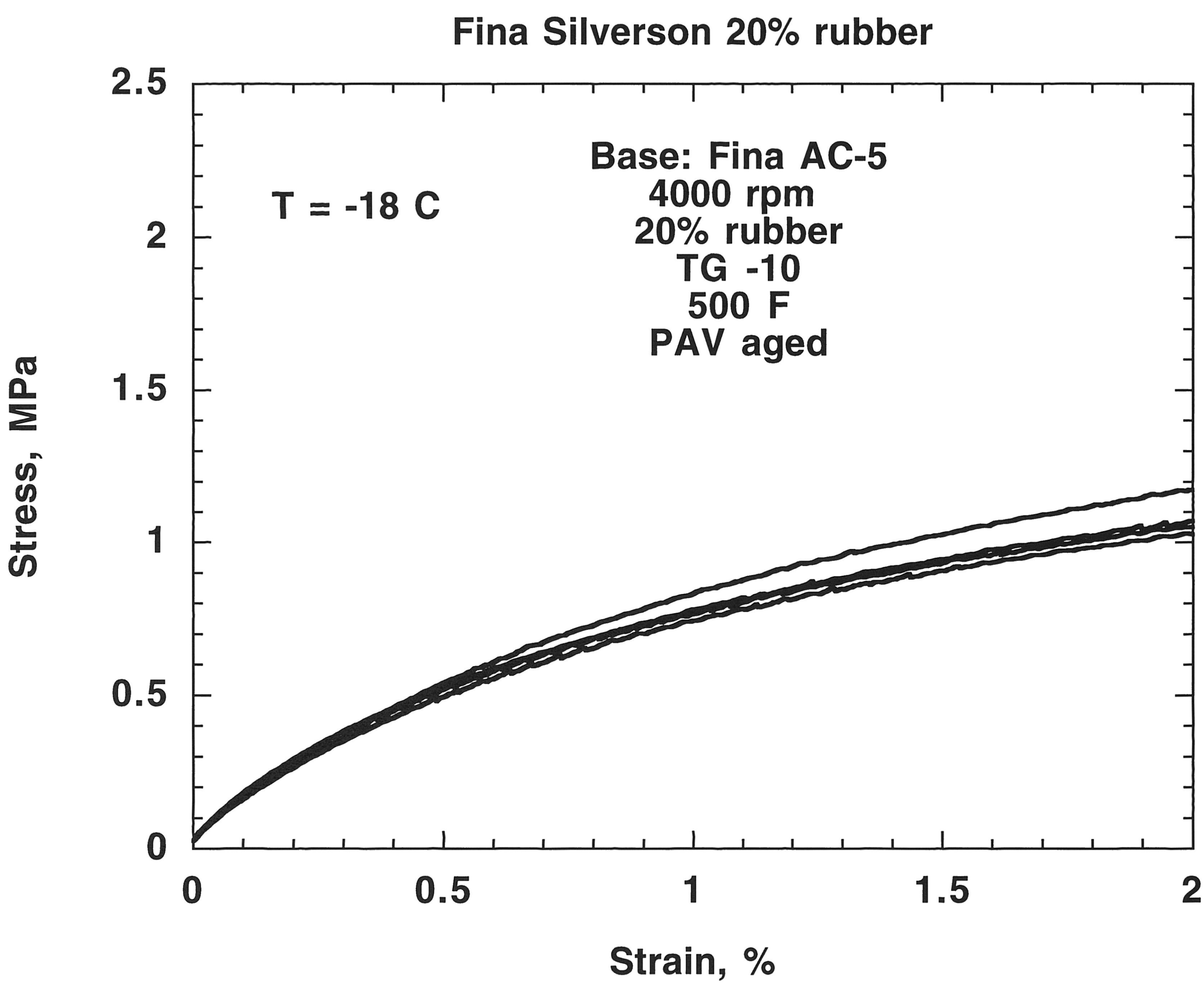


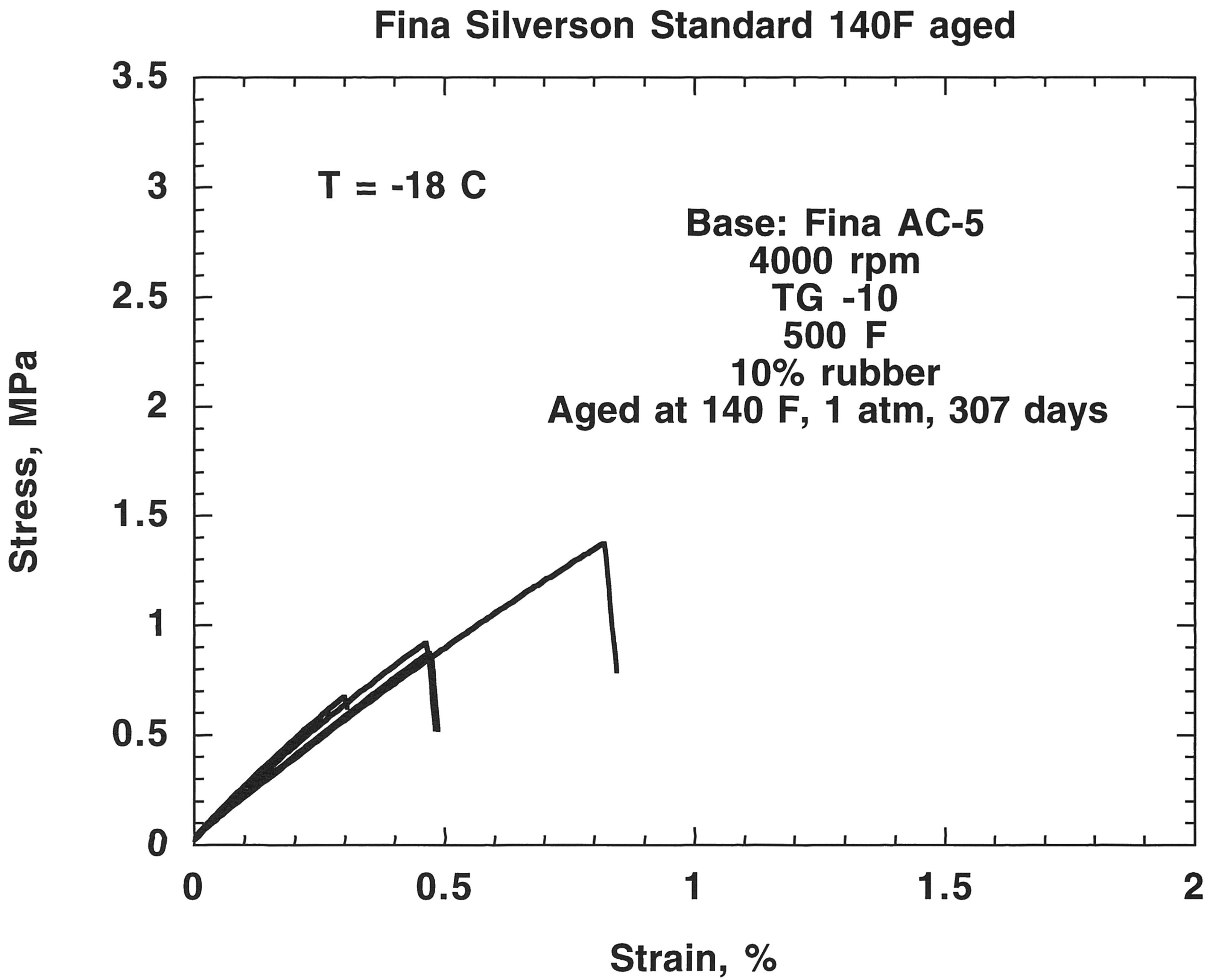
Fina Silverson 450 F
T = -18 C
Base: Fina AC-5
4000 rpm
10% rubber
TG -10
450 F
PAV aged
Stress, MPa
Strain, %
0
0.5
1
1.5
2
2.5
3
3.5
4


Fina Silverson 450 F
T = -18 C
Base: Fina AC-5
4000 rpm
10% rubber
TG -10
450 F
PAV aged
Stress, MPa
Strain, %
0
0.5
1
1.5
2
2.5
3
3.5
0
0.5
1
1.5
2

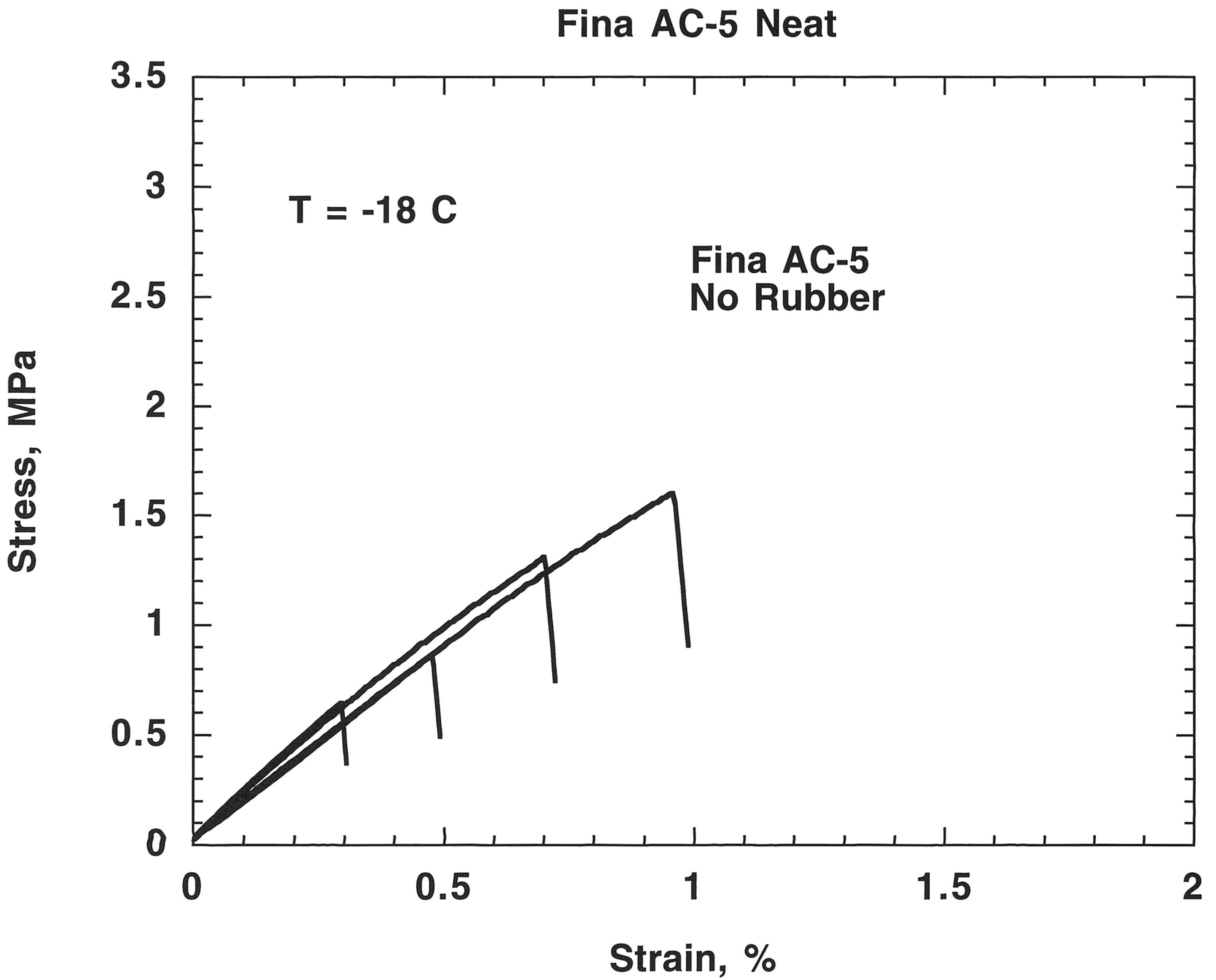

Fina AC-5 Silverson TG -40
T = -18 C
Base: Fina AC-5
TG -40
500 F
4000 rpm
10% rubber
PAV aged
Stress, MPa
Strain, %
0
0.5
1
1.5
2
2.5
3
3.5
0
0.5
1
1.5
2

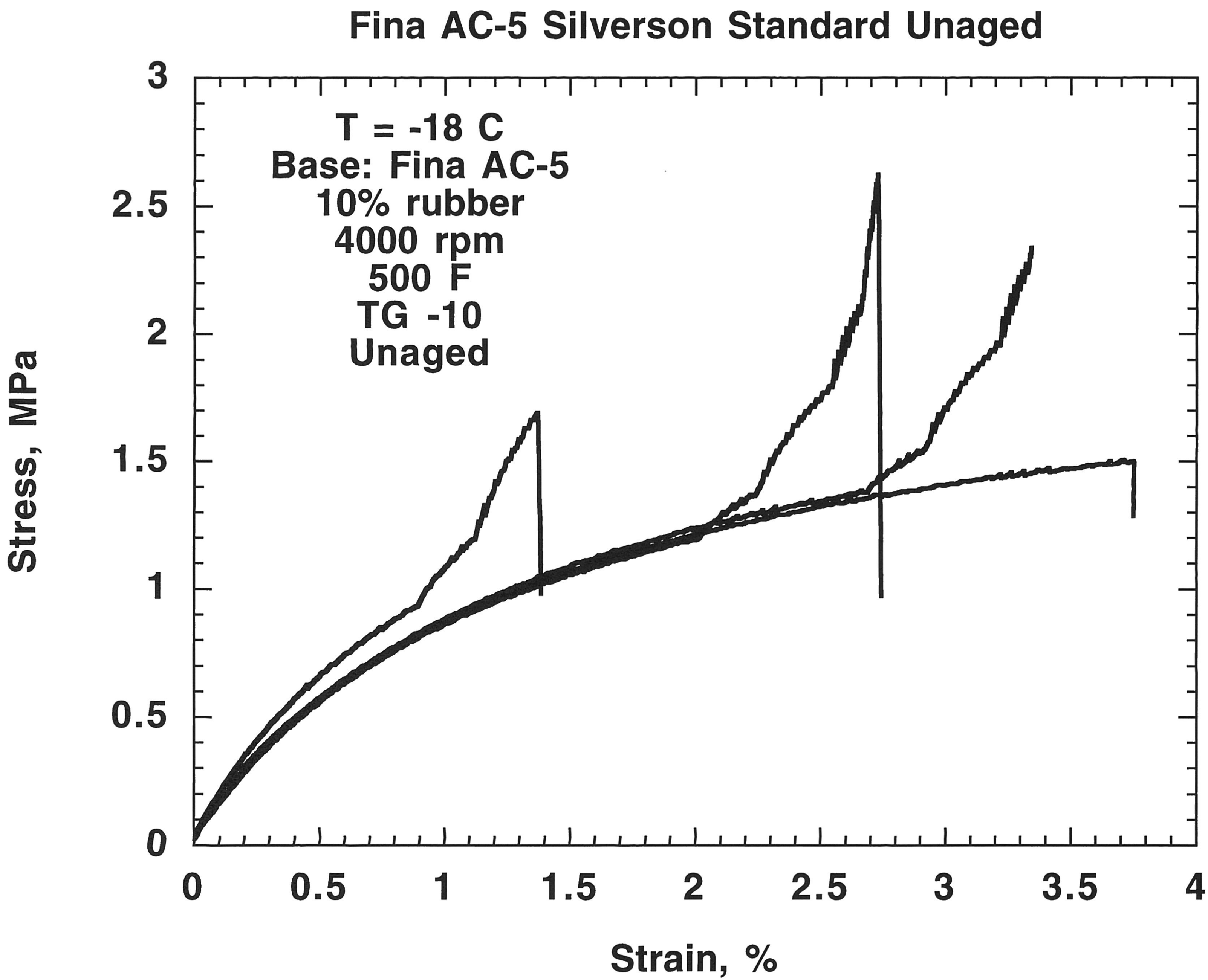

Fina Silverson 20% rubber
Base: Fina AC-5
4000 rpm
20% rubber
TG -10
500 F
PAV aged
T = -18 C
Stress, MPa
Strain, %
0
0.5
1
1.5
2
2.5
3
3.5
4

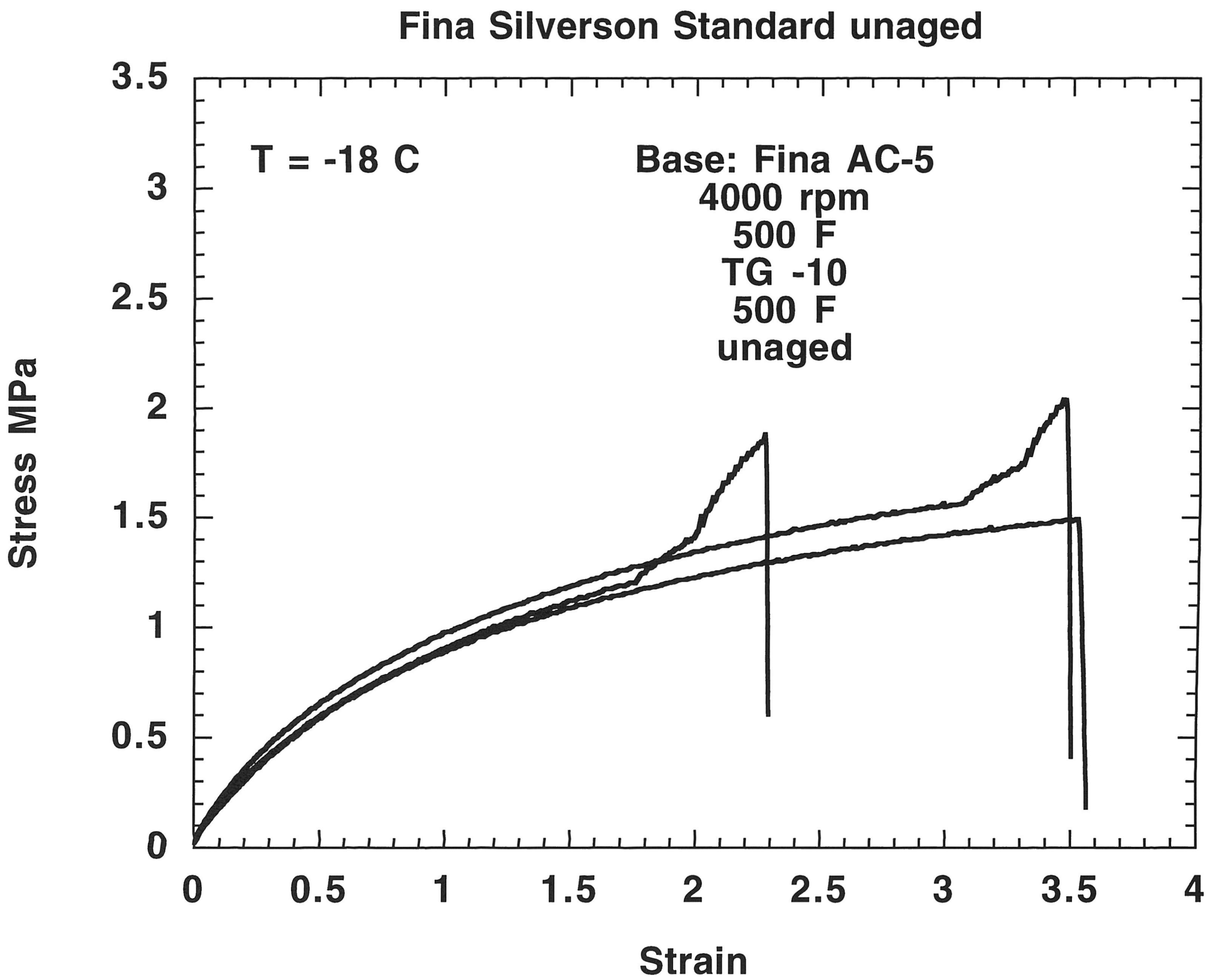

Fina Silverson 20% rubber
Stress, MPa
Strain, %
T = -18 C
Base: Fina AC-5
4000 rpm
20% rubber
TG -10
500 F
PAV aged
0
0.5
1
1.5
2
2.5

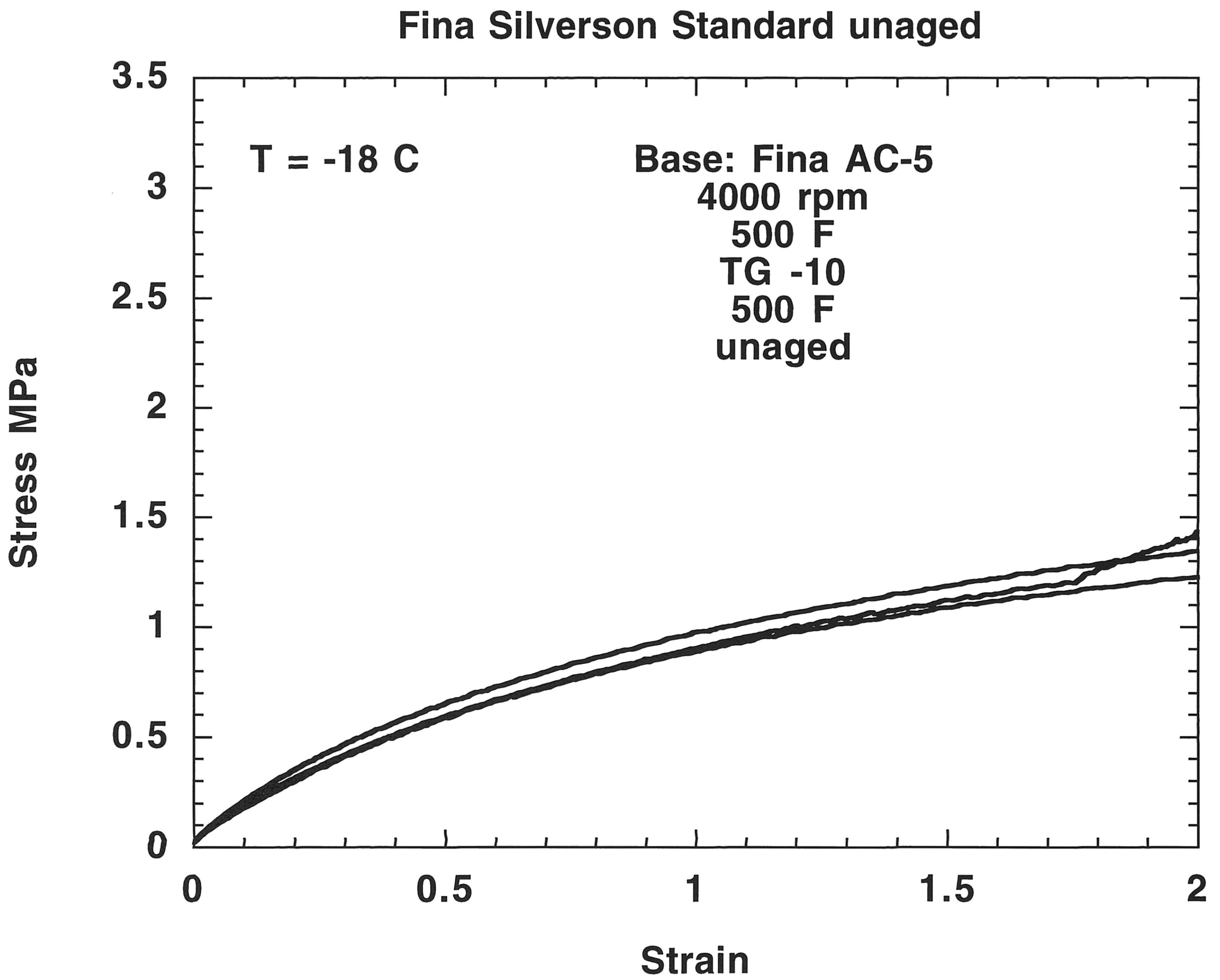


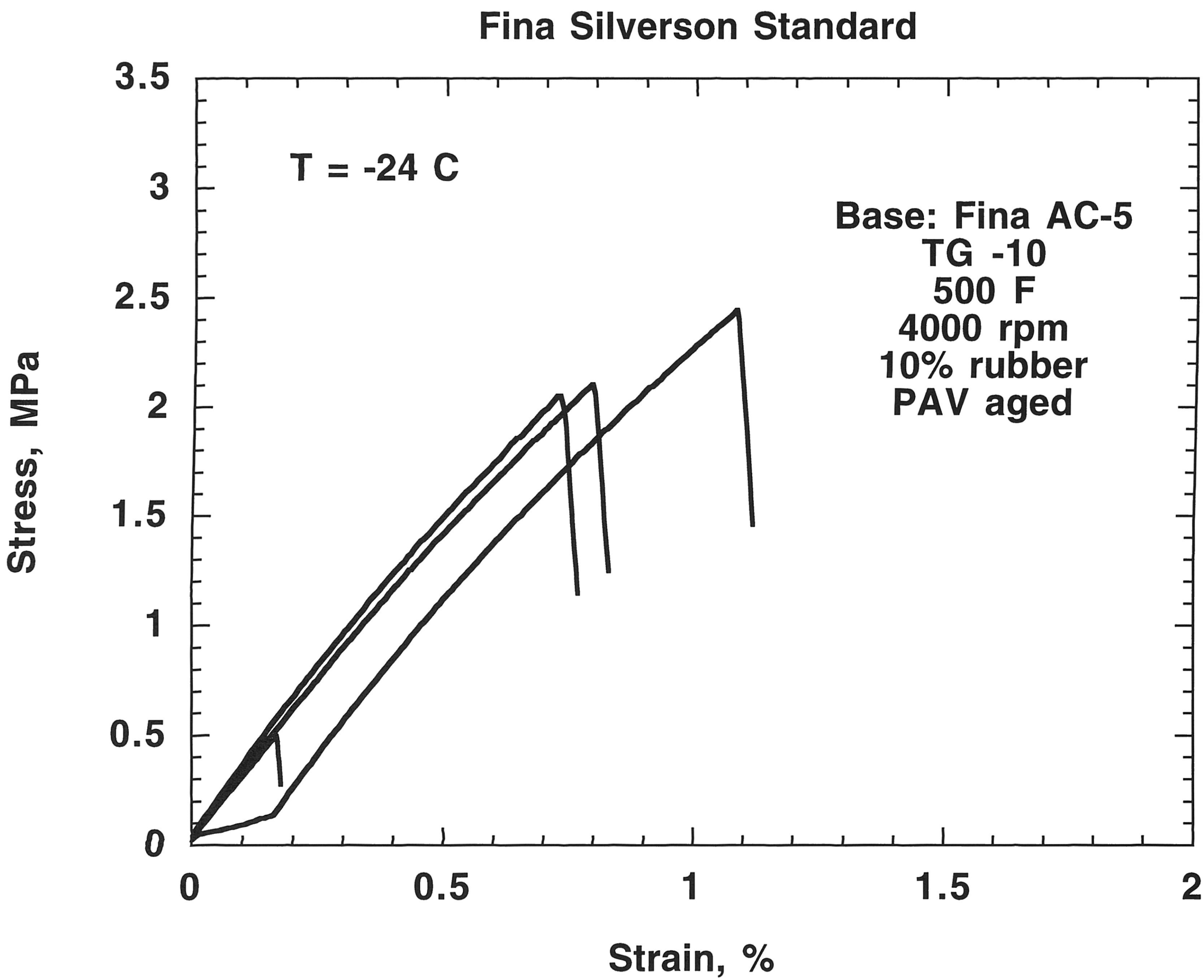
Fina Silverson Standard 140F aged
T = -18 C
Base: Fina AC-5
4000 rpm
TG -10
500 F
10% rubber
Aged at 140 F, 1 atm, 307 days
Stress, MPa
0
0.5
1
1.5
2
2.5
3
3.5
Strain, %
0
0.5
1
1.5
2


Fina AC-5 Neat
T = -18 C
Fina AC-5
No Rubber
Stress, MPa
3.5
3
2.5
2
1.5
1
0.5
0
0
0.5
1
1.5
2
Strain, %

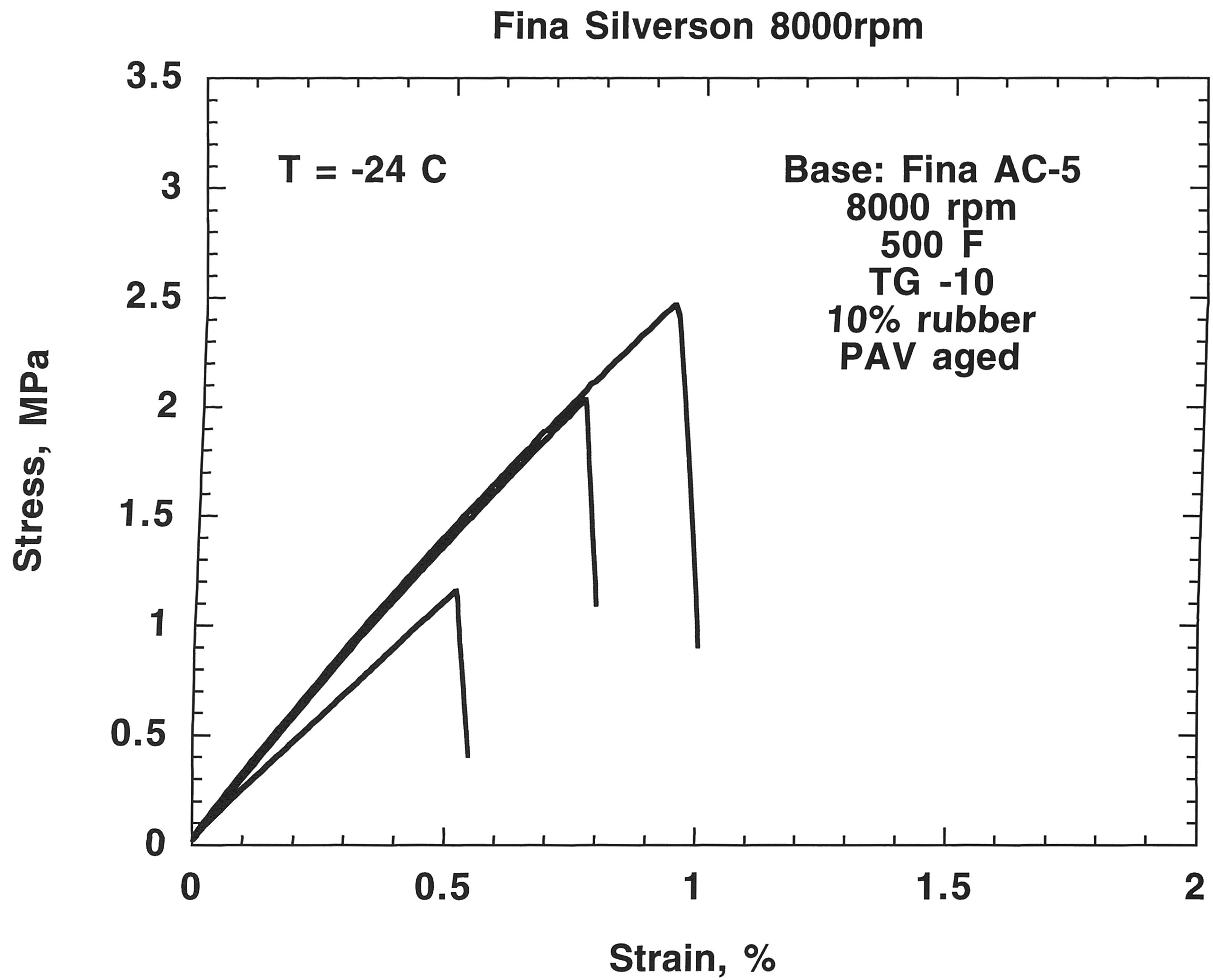

Fina AC-5 Silverson Standard Unaged
T = -18 C
Base: Fina AC-5
10% rubber
4000 rpm
500 F
TG -10
Unaged
Stress, MPa
0
0.5
1
1.5
2
2.5
3
Strain, %
0
0.5
1
1.5
2
2.5
3
3.5
4

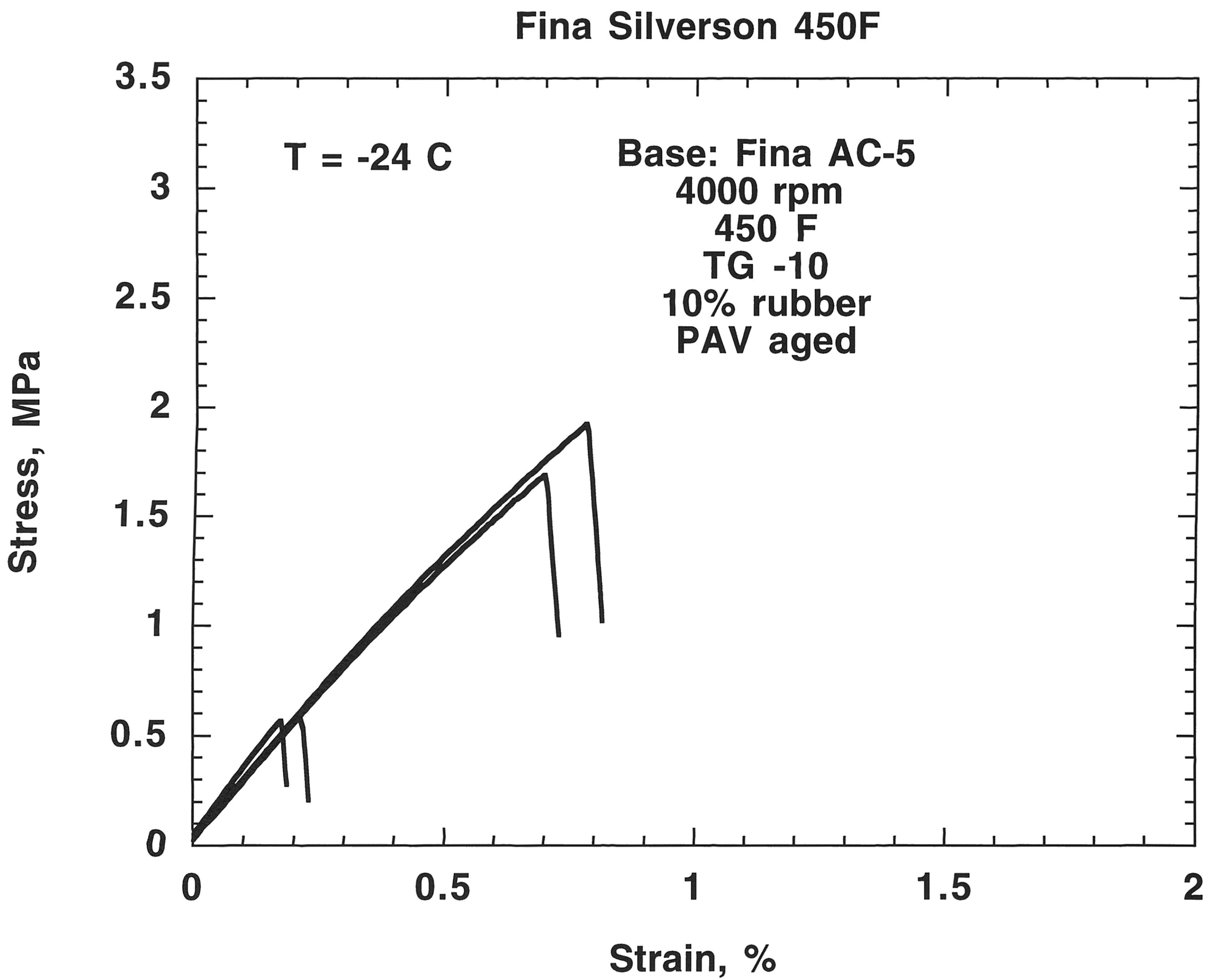

Fina Silverson Standard unaged
T = -18 C
Base: Fina AC-5
4000 rpm
500 F
TG -10
500 F
unaged
Stress MPa
Strain
0
0.5
1
1.5
2
2.5
3
3.5
4

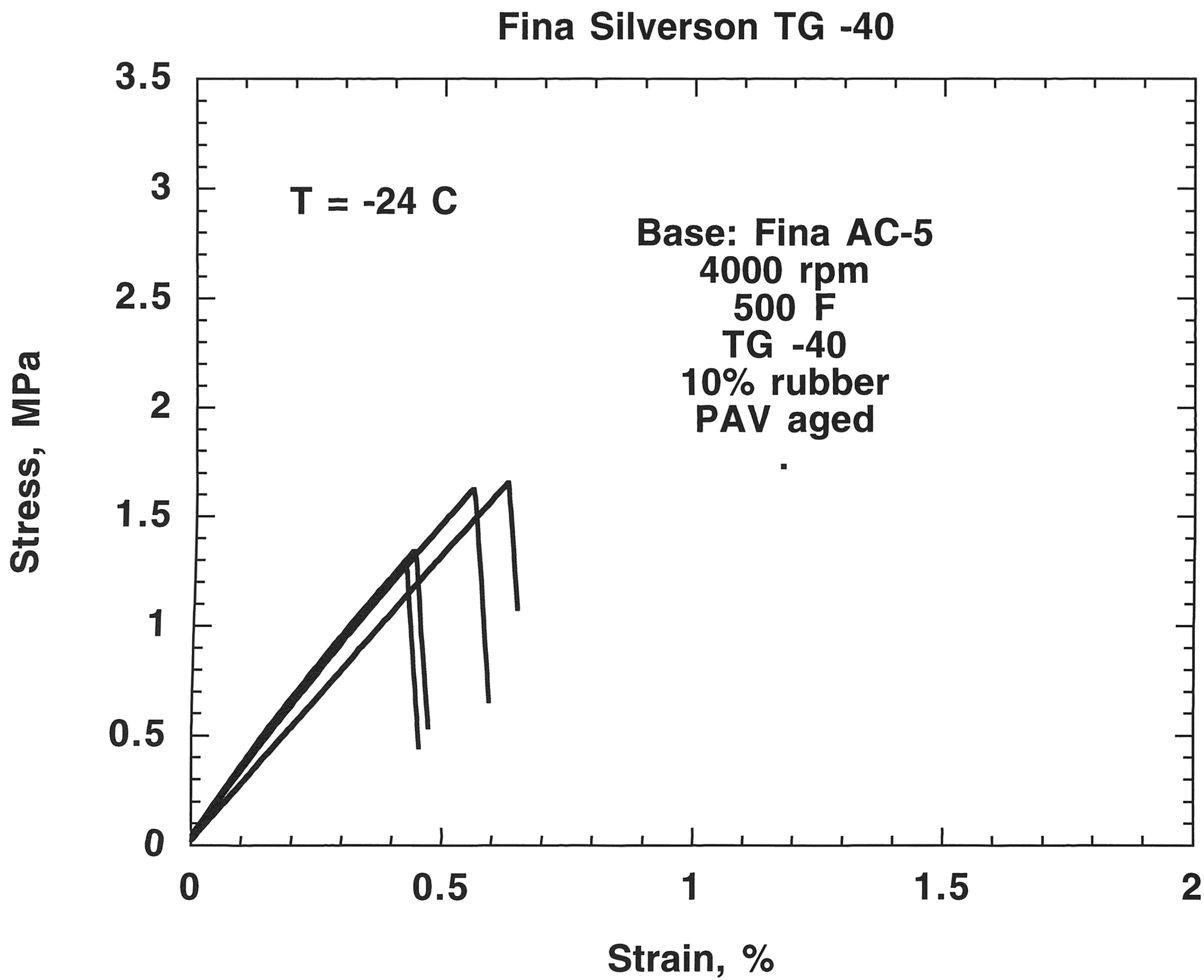

Fina Silverson Standard unaged
T = -18 C
Base: Fina AC-5
4000 rpm
500 F
TG -10
500 F
unaged
Stress MPa
3.5
3
2.5
2
1.5
1
0.5
0
0
0.5
1
1.5
2
Strain

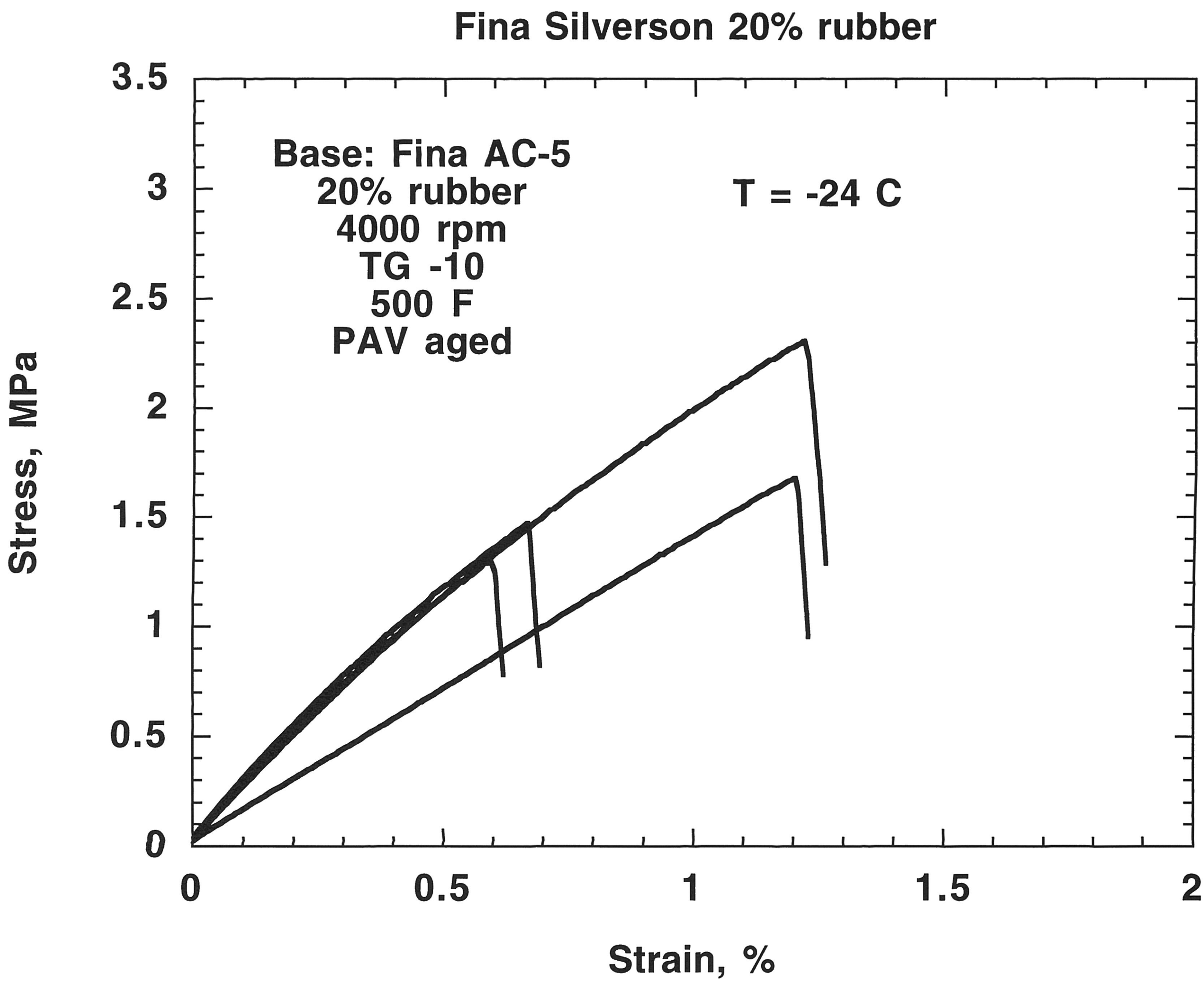


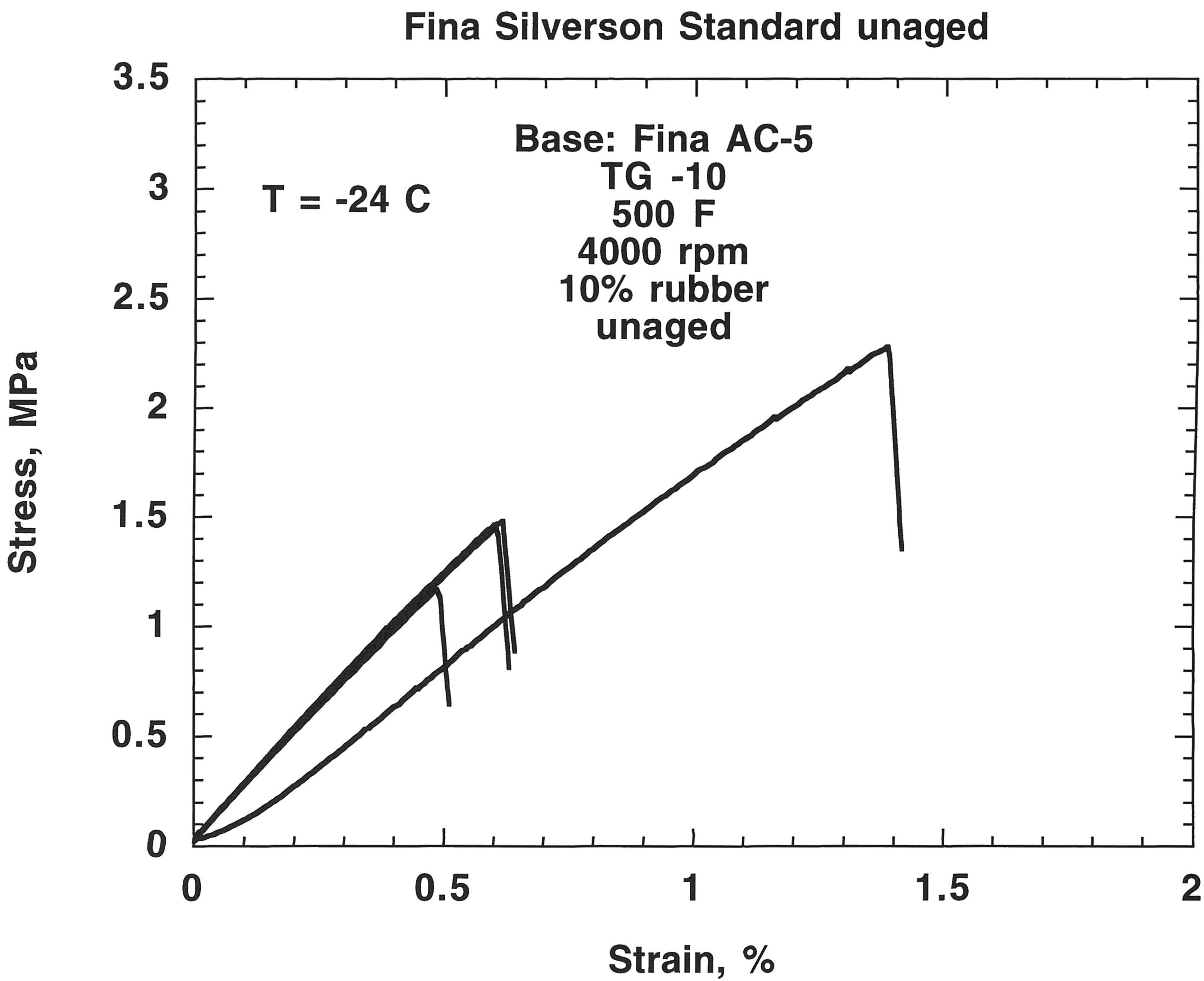
Fina Silverson Standard
T = -24 C
Base: Fina AC-5
TG -10
500 F
4000 rpm
10% rubber
PAV aged
Stress, MPa
0
0.5
1
1.5
2
2.5
3
3.5
Strain, %
0
0.5
1
1.5
2


Fina Silverson 8000rpm
T = -24 C
Base: Fina AC-5
8000 rpm
500 F
TG -10
10% rubber
PAV aged
Stress, MPa
Strain, %
0
0.5
1
1.5
2
2.5
3
3.5
0
0.5
1
1.5
2

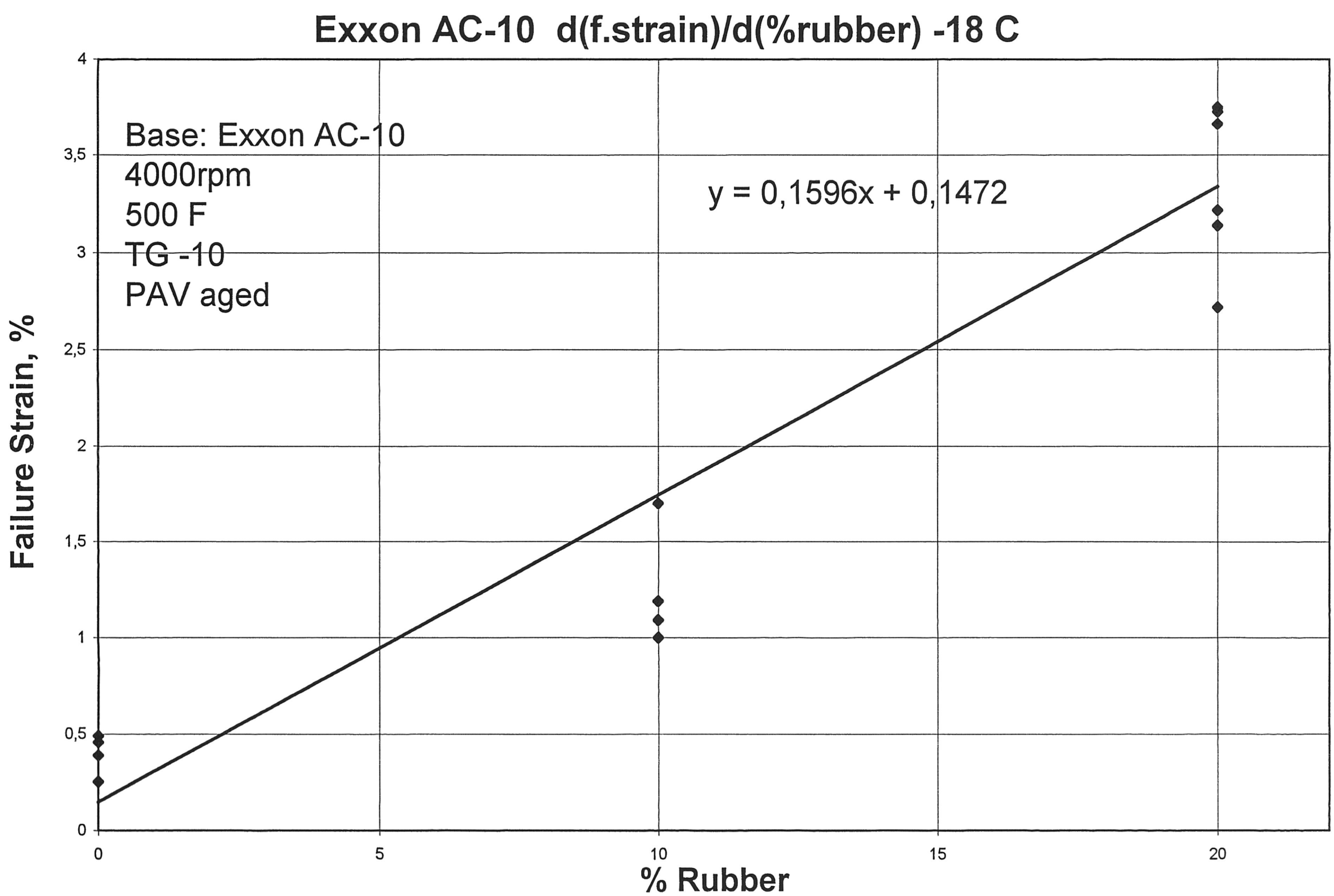

Fina Silverson 450F
T = -24 C
Base: Fina AC-5
4000 rpm
450 F
TG -10
10% rubber
PAV aged
Stress, MPa
0
0.5
1
1.5
2
2.5
3
3.5
Strain, %
0
0.5
1
1.5
2

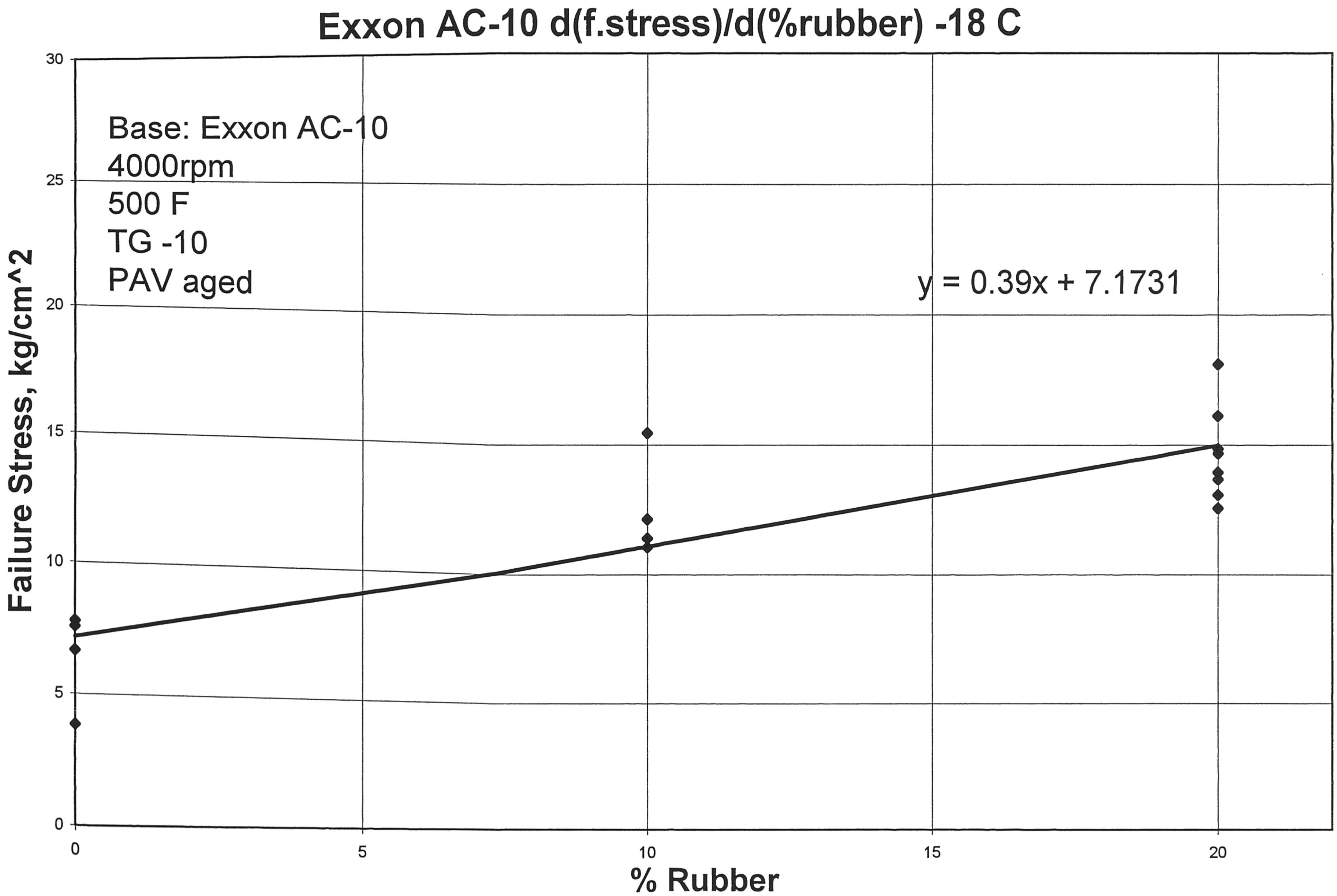

Fina Silverson TG -40
T = -24 C
Base: Fina AC-5
4000 rpm
500 F
TG -40
10% rubber
PAV aged
Stress, MPa
Strain, %
0
0.5
1
1.5
2
2.5
3
3.5
0
0.5
1
1.5
2


Fina Silverson 20% rubber
Base: Fina AC-5
20% rubber
4000 rpm
TG -10
500 F
PAV aged
T = -24 C
Stress, MPa
3.5
3
2.5
2
1.5
1
0.5
0
Strain, %
0.5
1
1.5
2

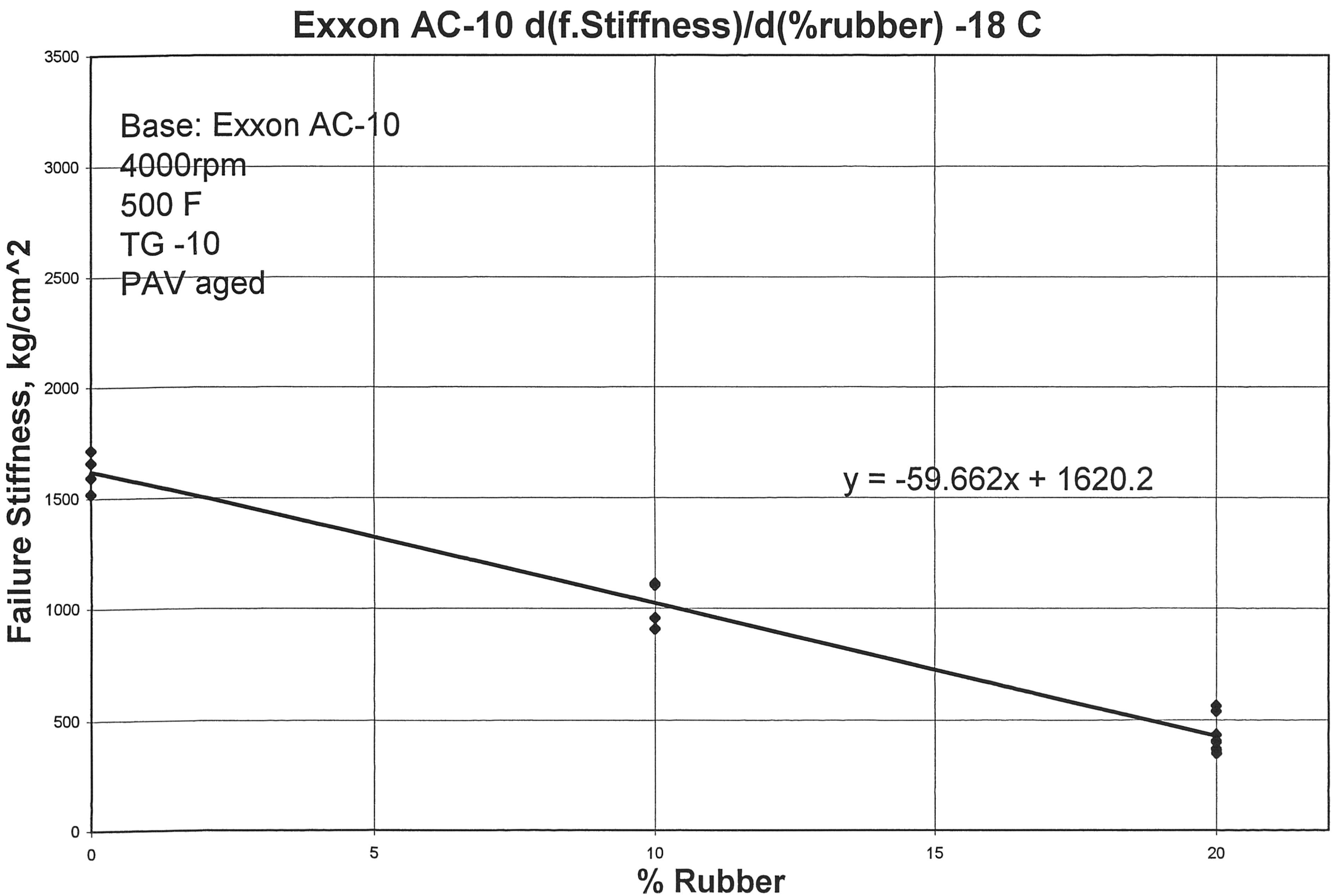

Fina Silverson Standard unaged
Base: Fina AC-5
TG -10
500 F
4000 rpm
10% rubber
unaged
T = -24 C
Stress, MPa
Strain, %
0
0.5
1
1.5
2
2.5
3
3.5
0
0.5
1
1.5
2

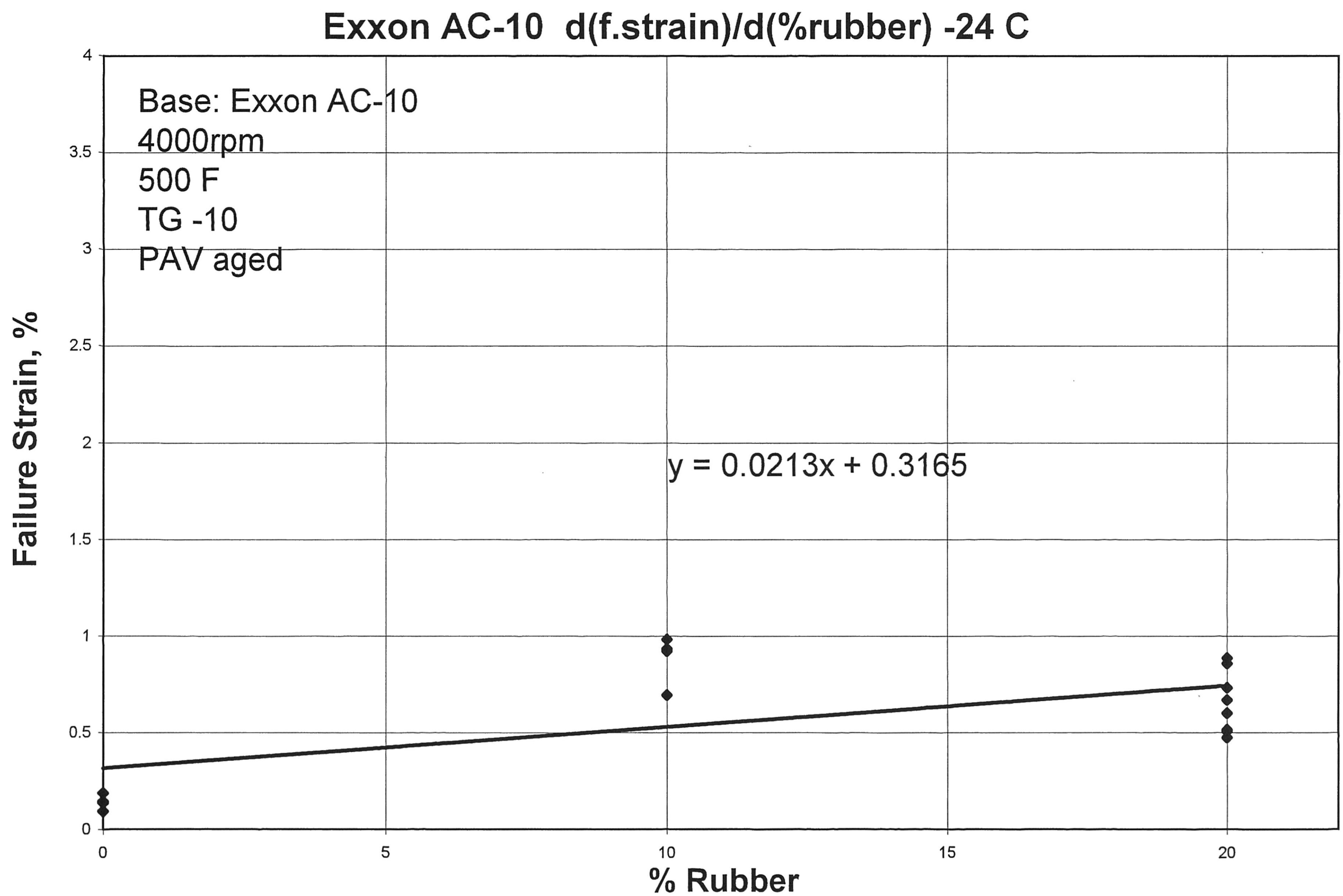
Appendix G: Rubber Content Dependence of Failure Properties

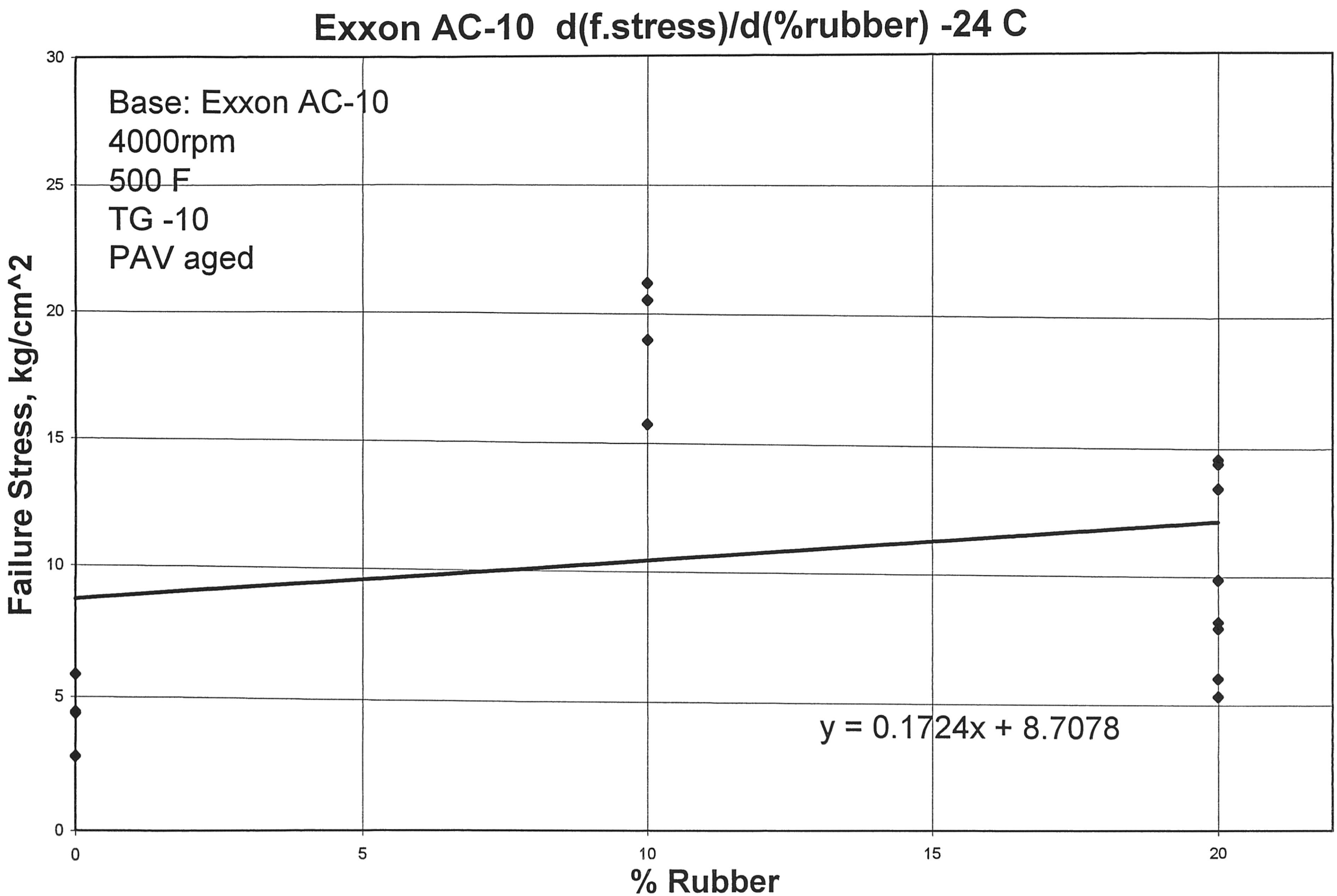

Exxon AC-10 d(f.strain)/d(%rubber) -18 C
Base: Exxon AC-10
4000rpm
500 F
TG -10
PAV aged
y = 0,1596x + 0,1472
Failure Strain, %
% Rubber
0
0,5
1
1,5
2
2,5
3
3,5
4
0
5
10
15
20



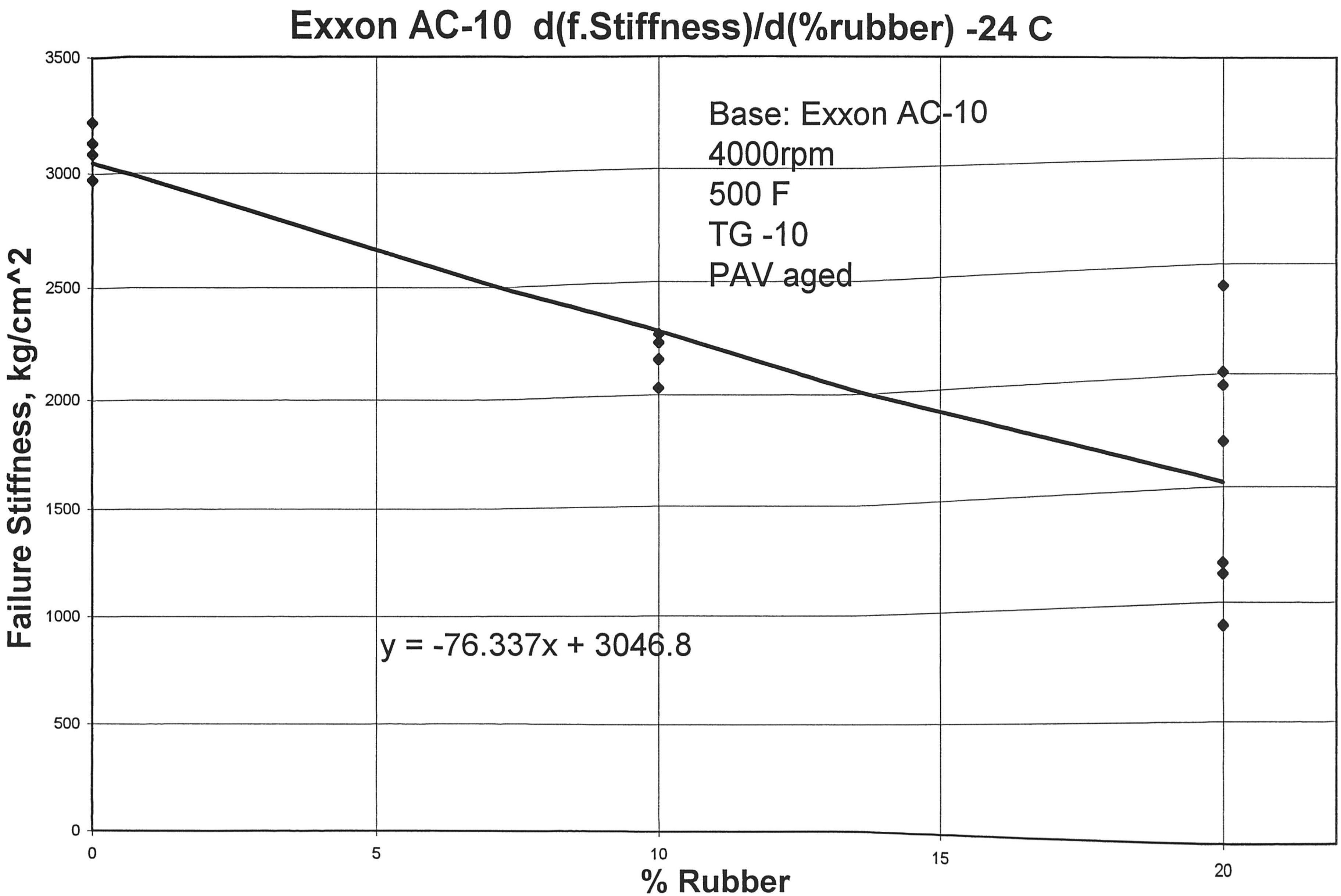
Exxon AC-10 d(f.stress)/d(%rubber) -18 C
Base: Exxon AC-10
4000rpm
500 F
TG -10
PAV aged
y = 0.39x + 7.1731
Failure Stress, kg/cm^2
% Rubber
0
5
10
15
20
25
30


Exxon AC-10 d(f.Stiffness)/d(%rubber) -18 C
Base: Exxon AC-10
4000rpm
500 F
TG -10
PAV aged
y = -59.662x + 1620.2
Failure Stiffness, kg/cm^2
% Rubber
0
500
1000
1500
2000
2500
3000
3500
0
5
10
15
20

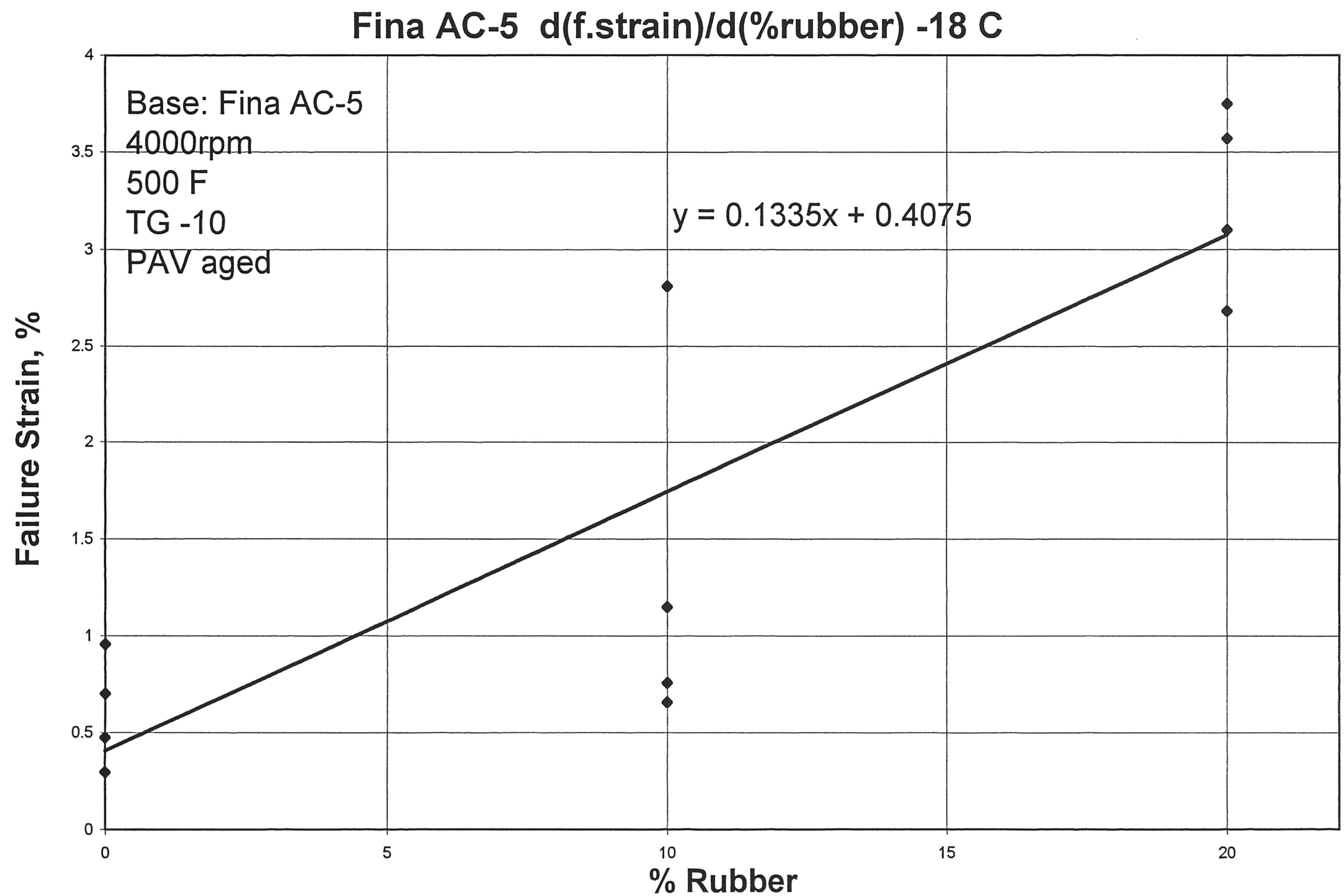

Exxon AC-10 d(f.strain)/d(%rubber) -24 C
Base: Exxon AC-10
4000rpm
500 F
TG -10
PAV aged
y = 0.0213x + 0.3165
Failure Strain, %
% Rubber
0
0.5
1
1.5
2
2.5
3
3.5
4
0
5
10
15
20



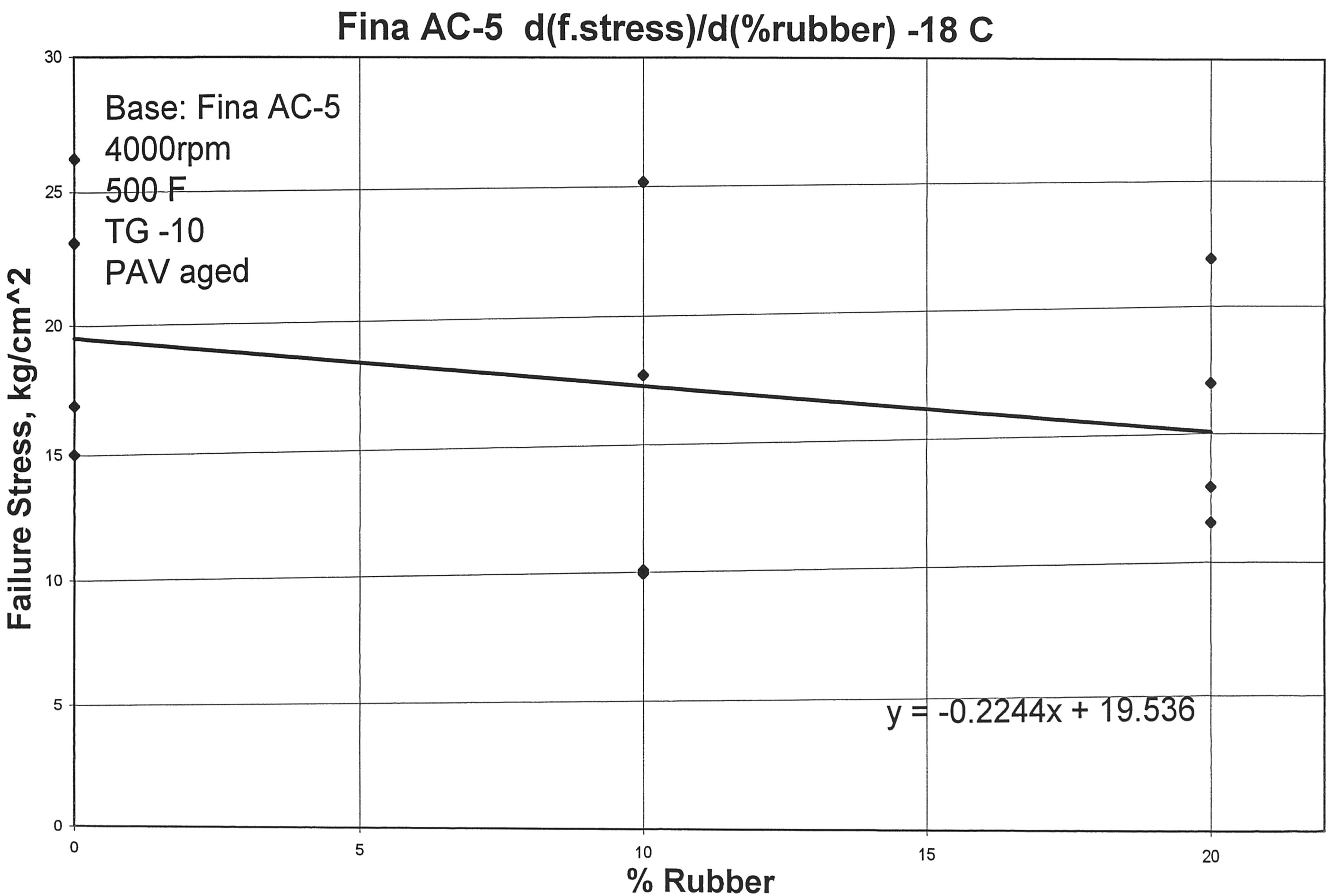
Exxon AC-10 d(f.stress)/d(%rubber) -24 C
Base: Exxon AC-10
4000rpm
500 F
TG -10
PAV aged
Failure Stress, kg/cm^2
% Rubber
y = 0.1724x + 8.7078
0
5
10
15
20
25
30
0
5
10
15
20

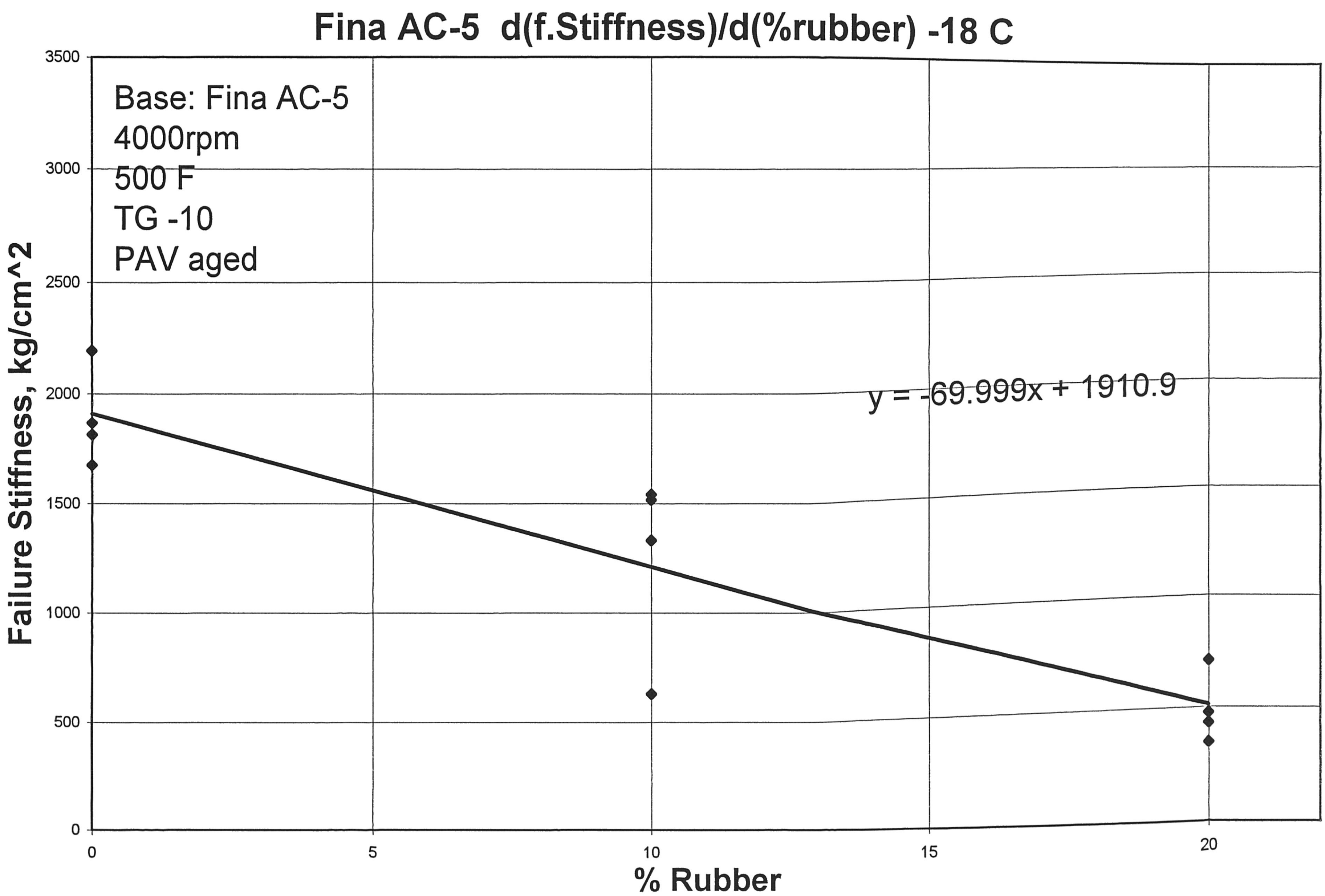


Exxon AC-10 d(f.Stiffness)/d(%rubber) -24 C
Base: Exxon AC-10
4000rpm
500 F
TG -10
PAV aged
y = -76.337x + 3046.8
Failure Stiffness, kg/cm^2
% Rubber
3500
3000
2500
2000
1500
1000
500
0
5
10
15
20

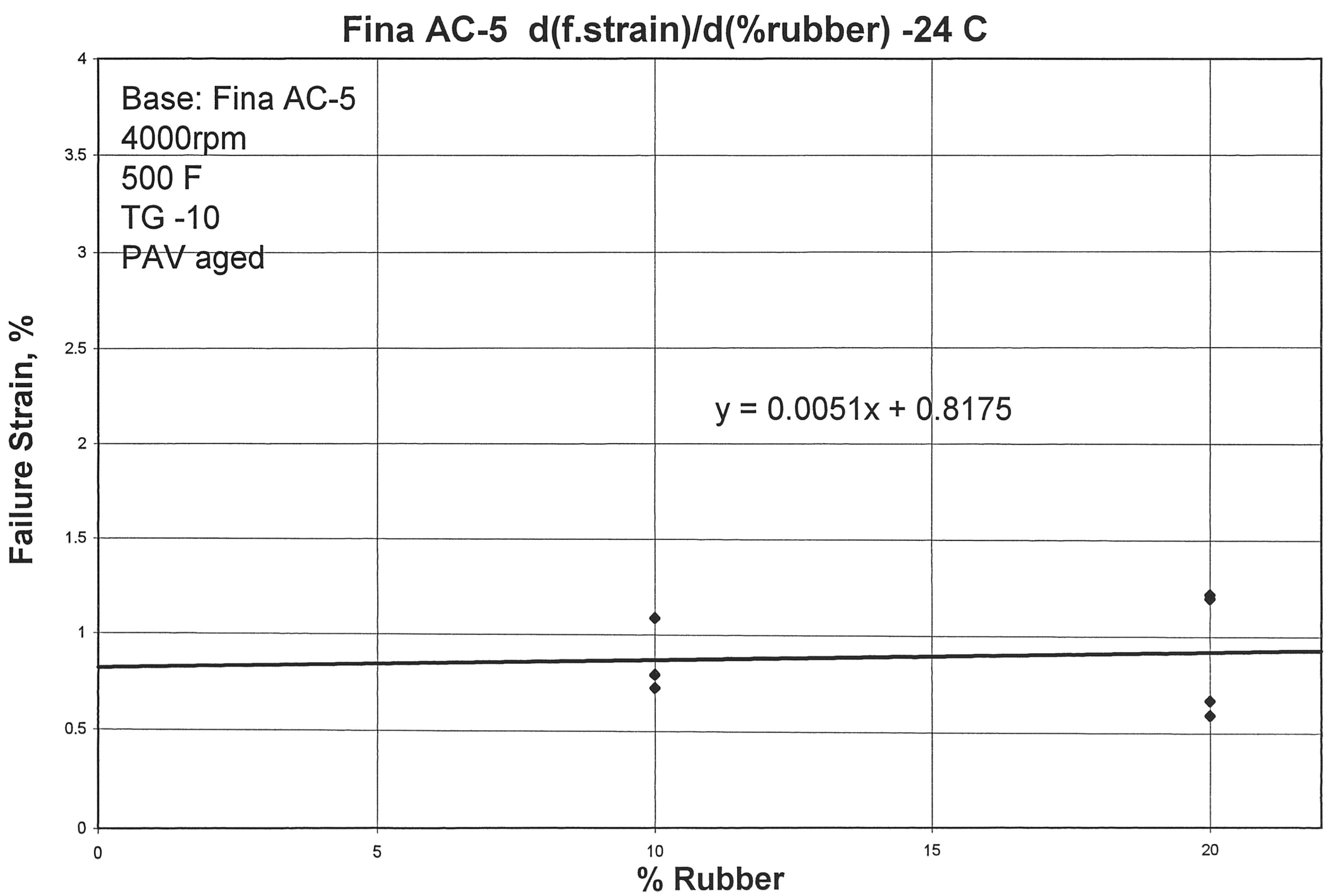


Fina AC-5 d(f.strain)/d(%rubber) -18 C
Base: Fina AC-5
4000rpm
500 F
TG -10
PAV aged
y = 0.1335x + 0.4075
Failure Strain, %
% Rubber
0
0.5
1
1.5
2
2.5
3
3.5
4
0
5
10
15
20

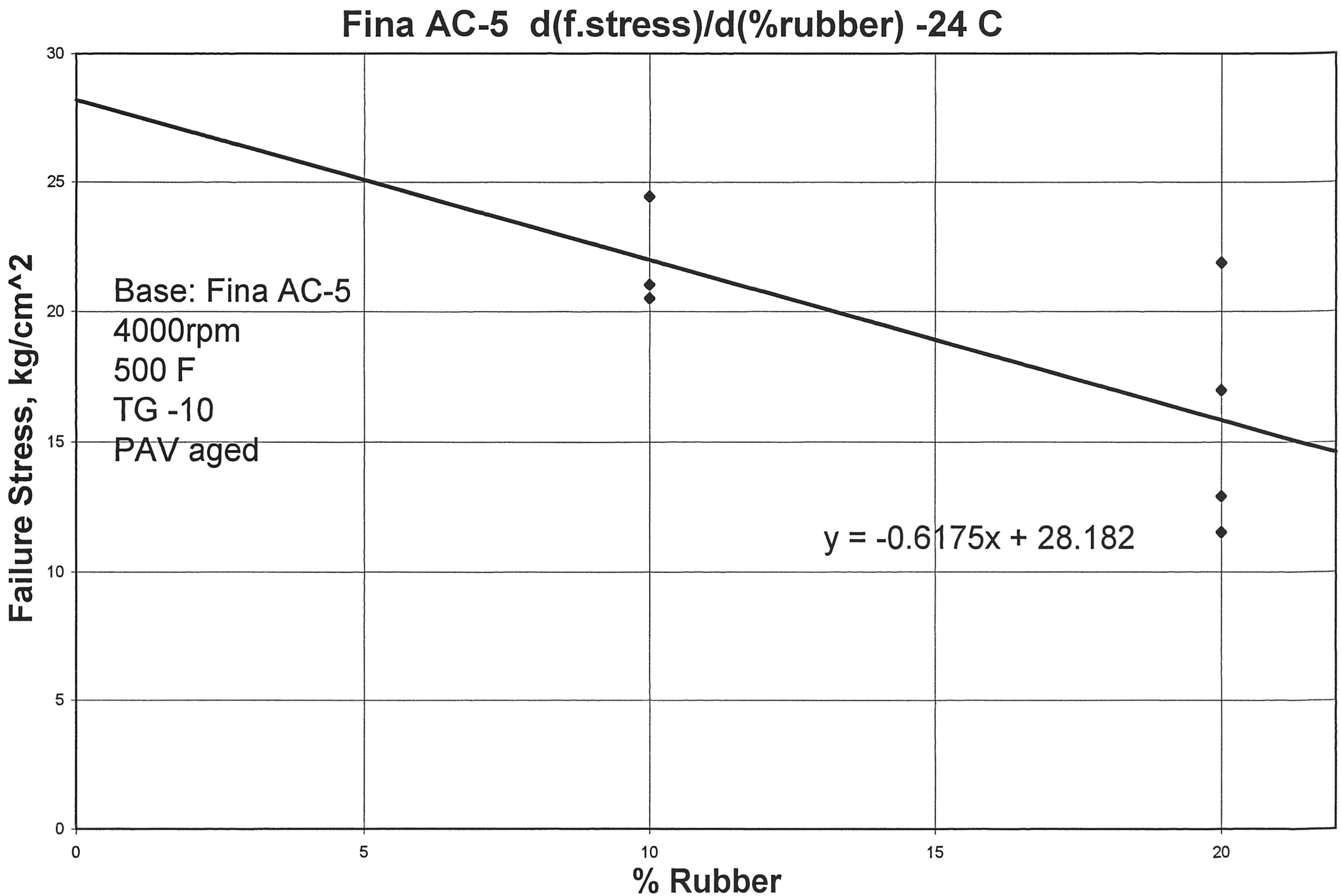

Fina AC-5 d(f.stress)/d(%rubber) -18 C
Base: Fina AC-5
4000rpm
500 F
TG -10
PAV aged
y = -0.2244x + 19.536
Failure Stress, kg/cm^2
% Rubber
0
5
10
15
20
25
30



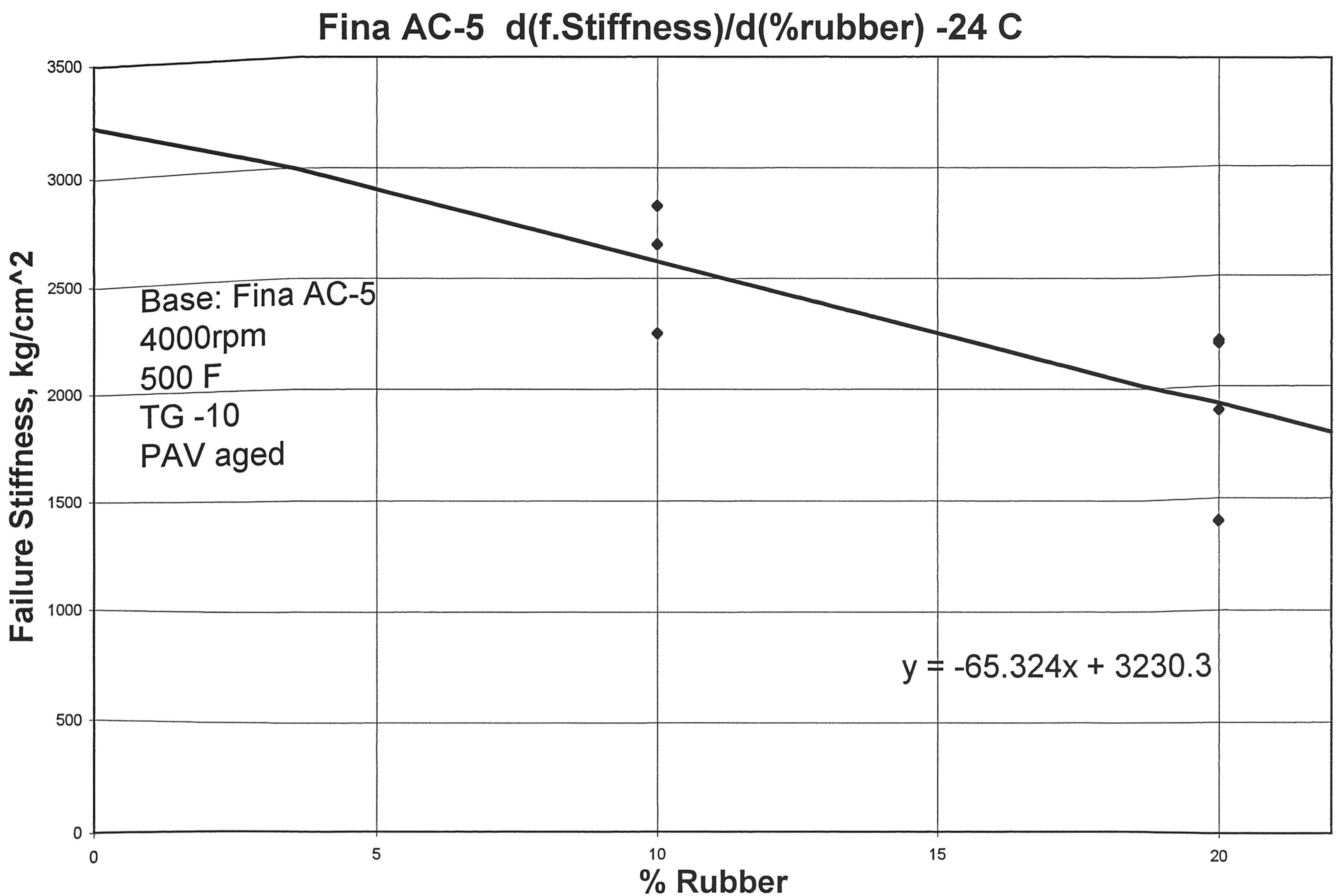
Fina AC-5 d(f.Stiffness)/d(%rubber) -18 C
Base: Fina AC-5
4000rpm
500 F
TG -10
PAV aged
y = -69.999x + 1910.9
Failure Stiffness, kg/cm^2
% Rubber
3500
3000
2500
2000
1500
1000
500
0
0
5
10
15
20



Fina AC-5 d(f.strain)/d(%rubber) -24 C
Base: Fina AC-5
4000rpm
500 F
TG -10
PAV aged
y = 0.0051x + 0.8175
Failure Strain, %
% Rubber
0
0.5
1
1.5
2
2.5
3
3.5
4
5
10
15
20

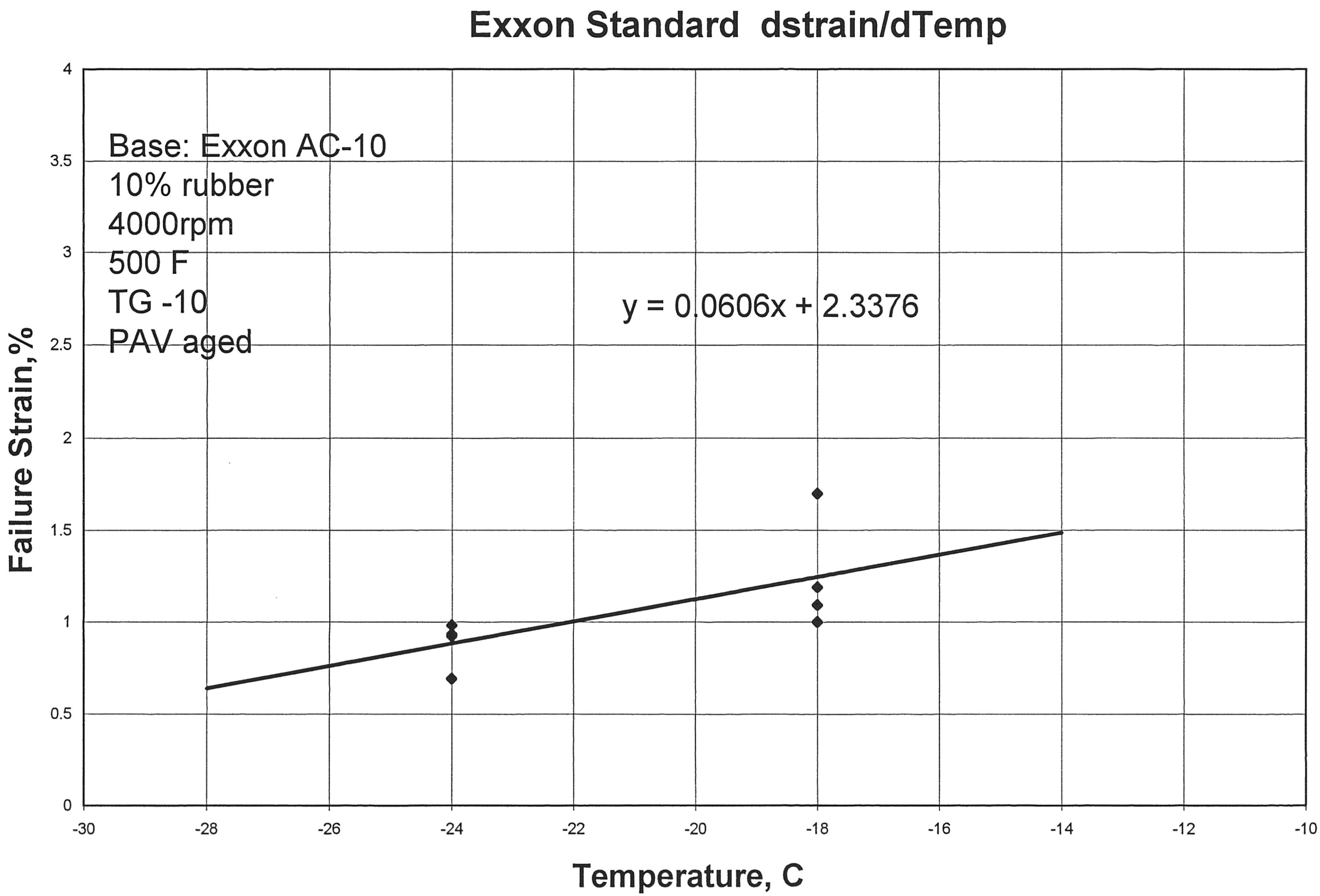


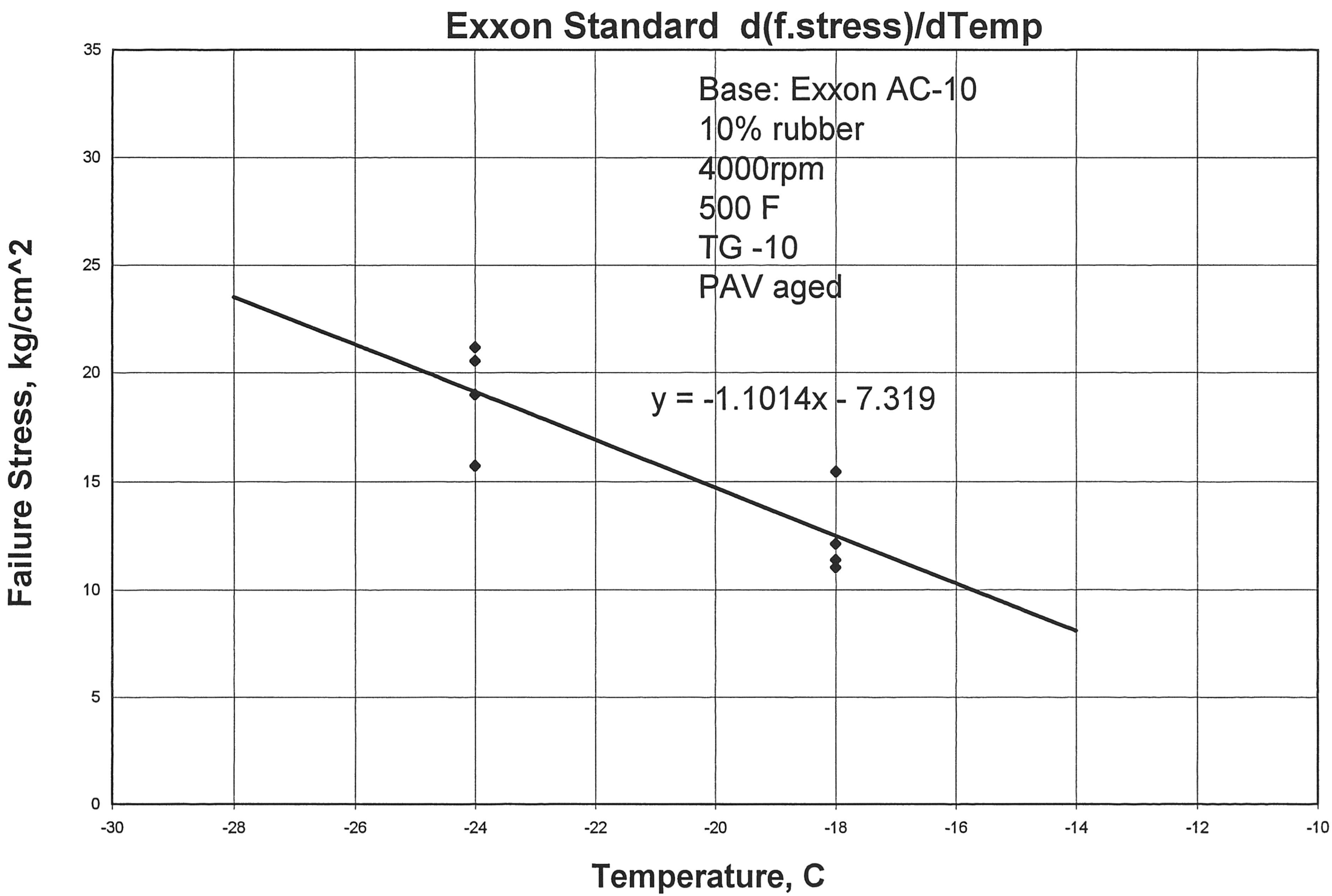
Fina AC-5 d(f.stress)/d(%rubber) -24 C
Failure Stress, kg/cm^2
% Rubber
Base: Fina AC-5
4000rpm
500 F
TG -10
PAV aged
y = -0.6175x + 28.182
0
5
10
15
20
25
30



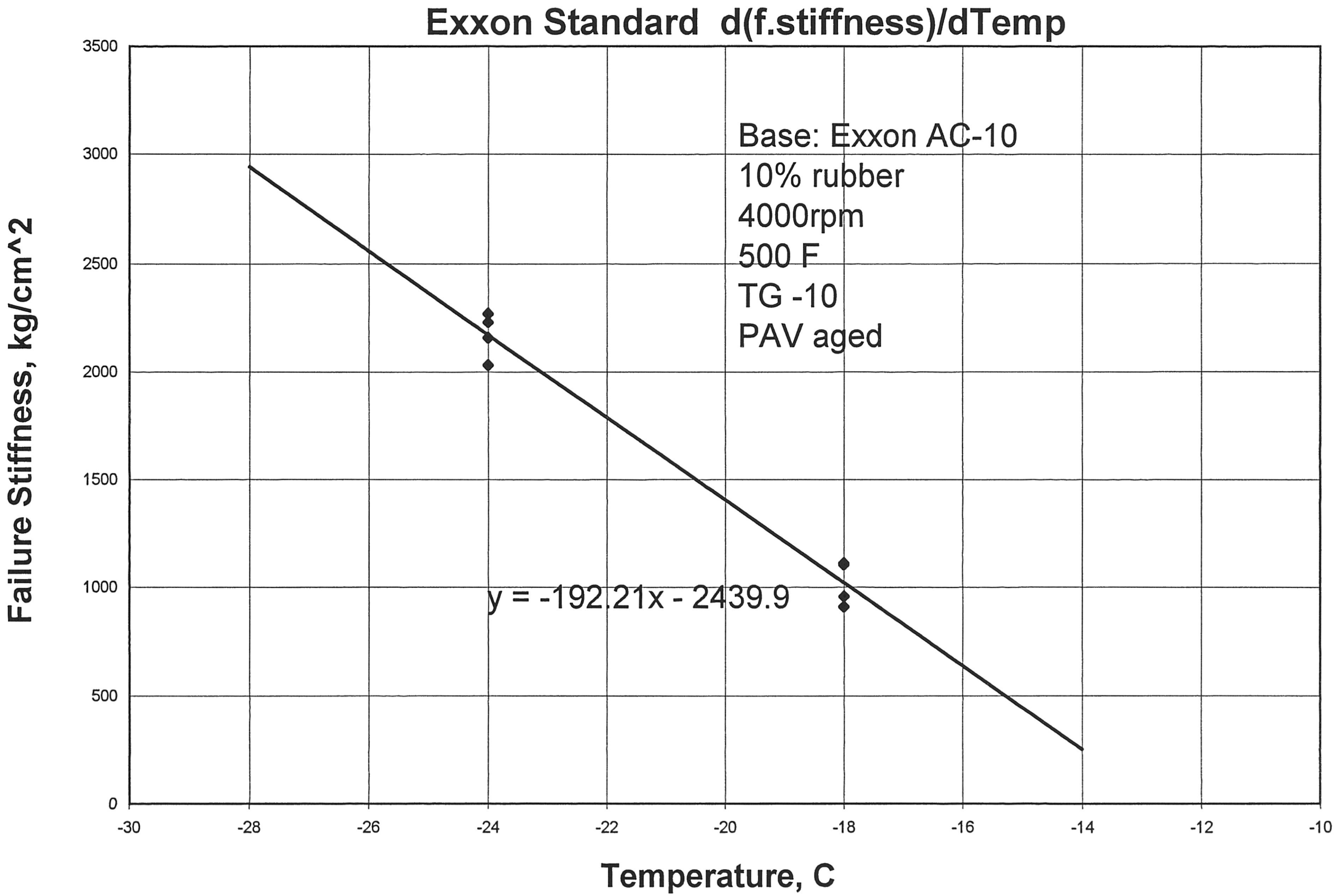
Fina AC-5 d(f.Stiffness)/d(%rubber) -24 C
Failure Stiffness, kg/cm^2
3500
3000
2500
2000
1500
1000
500
0
0
5
10
15
20
% Rubber
Base: Fina AC-5
4000rpm
500 F
TG -10
PAV aged
y = -65.324x + 3230.3

Appendix H: Temperature Dependence of Failure Properties

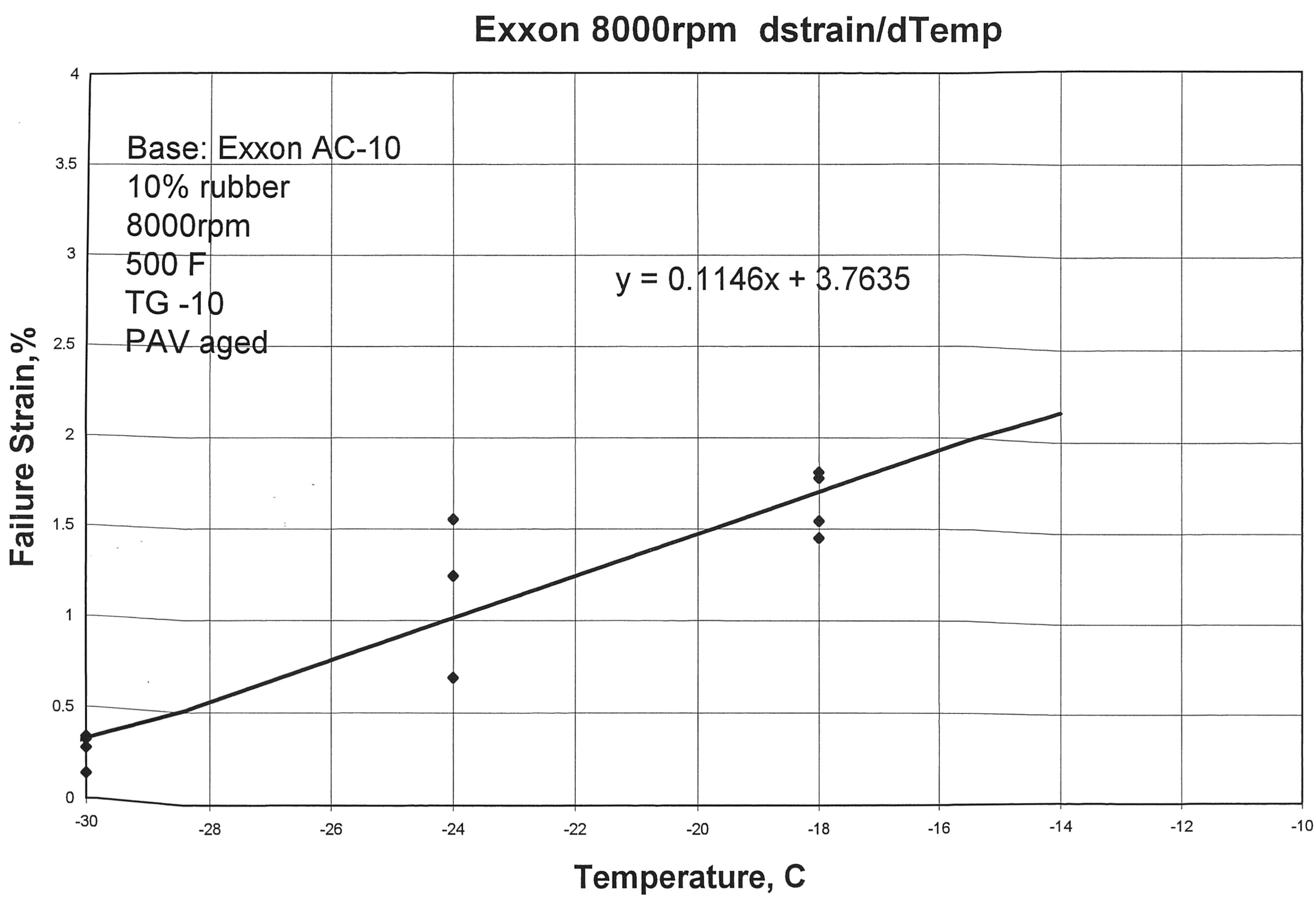

Exxon Standard dstrain/dTemp
Base: Exxon AC-10
10% rubber
4000rpm
500 F
TG -10
PAV aged
y = 0.0606x + 2.3376
Failure Strain,%
Temperature, C
4
3.5
3
2.5
2
1.5
1
0.5
0
-30
-28
-26
-24
-22
-20
-18
-16
-14
-12
-10

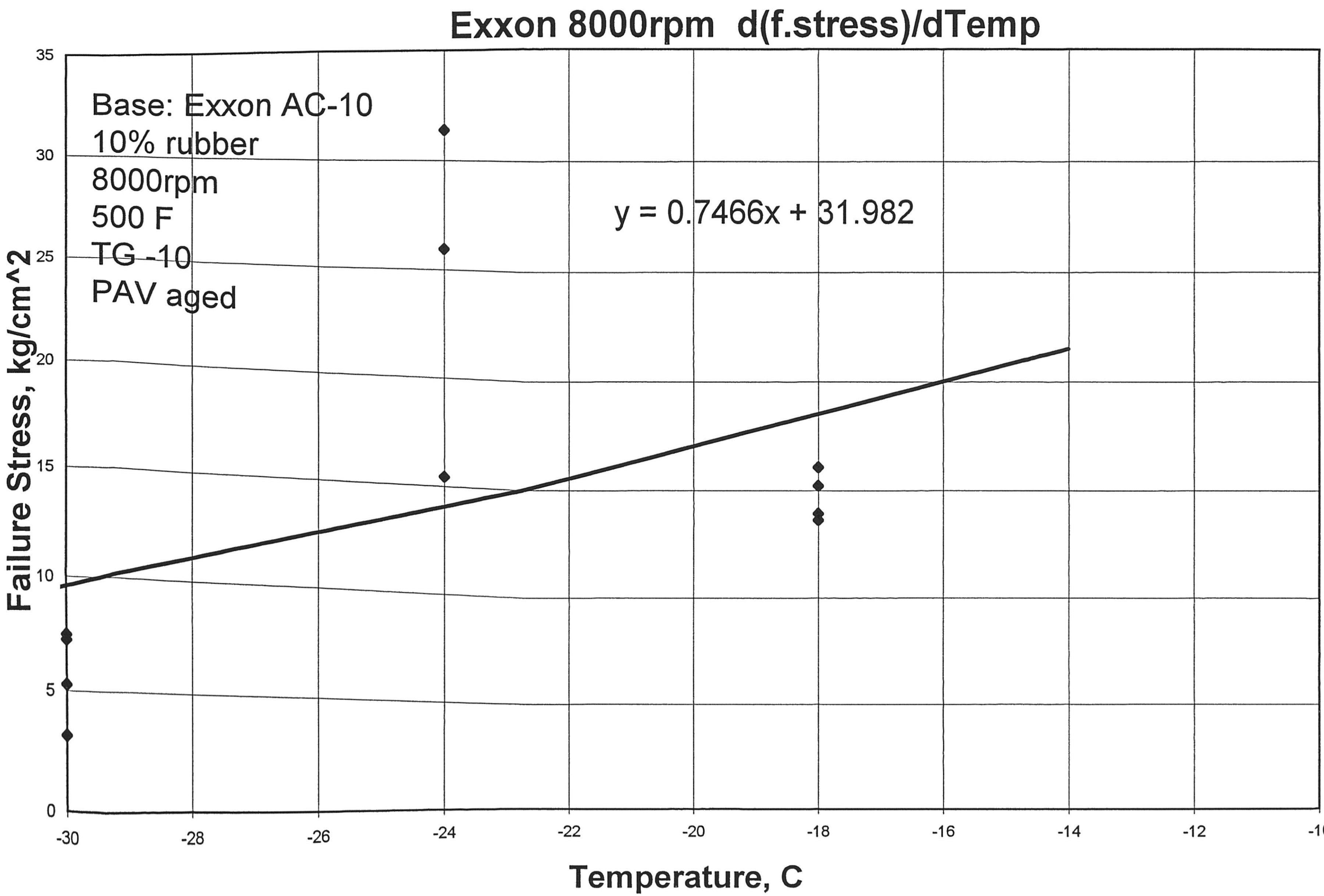


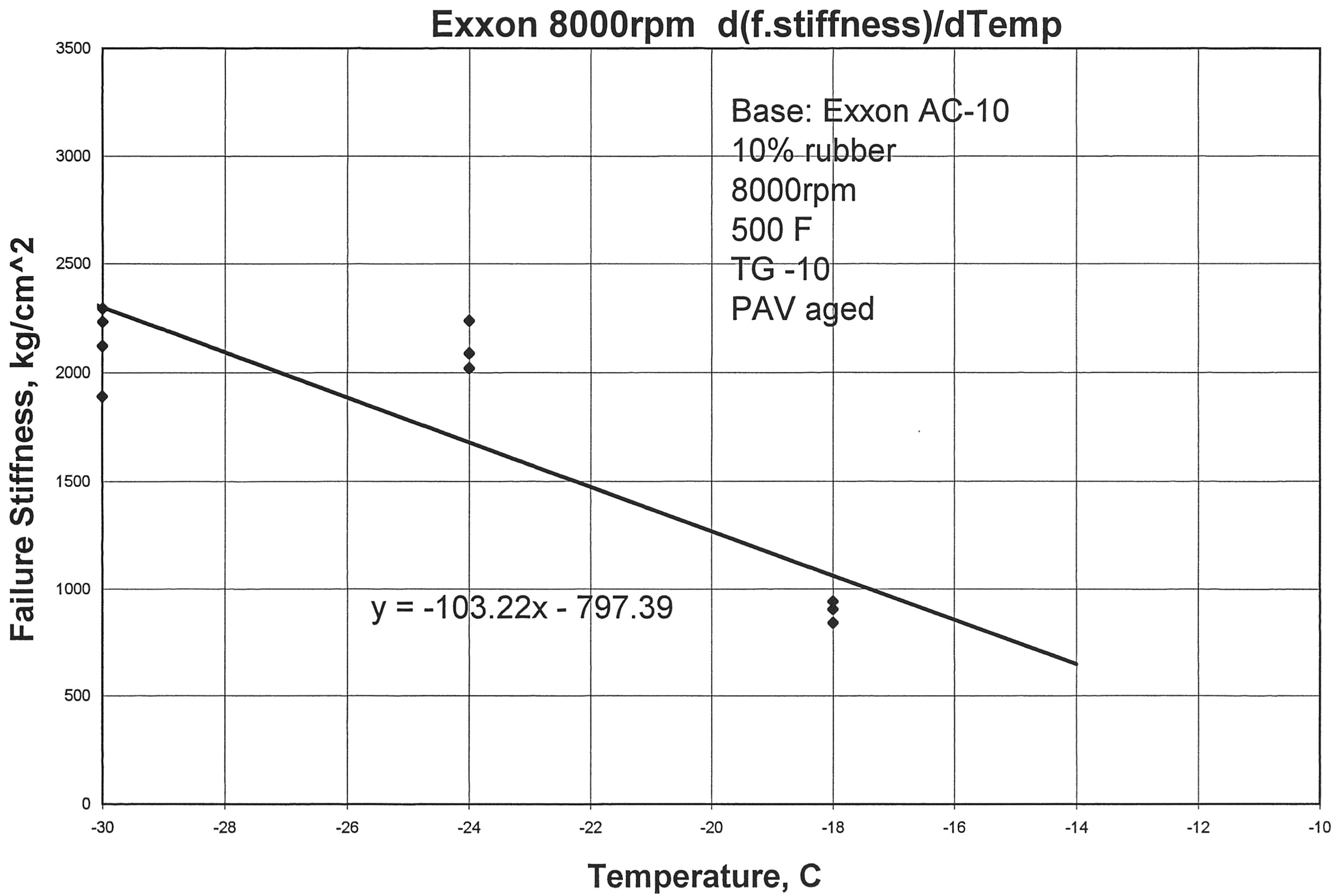
Exxon Standard d(f.stress)/dTemp
Base: Exxon AC-10
10% rubber
4000rpm
500 F
TG -10
PAV aged
y = -1.1014x - 7.319
Failure Stress, kg/cm^2
0
5
10
15
20
25
30
35
-30
-28
-26
-24
-22
-20
-18
-16
-14
-12
-10
Temperature, C

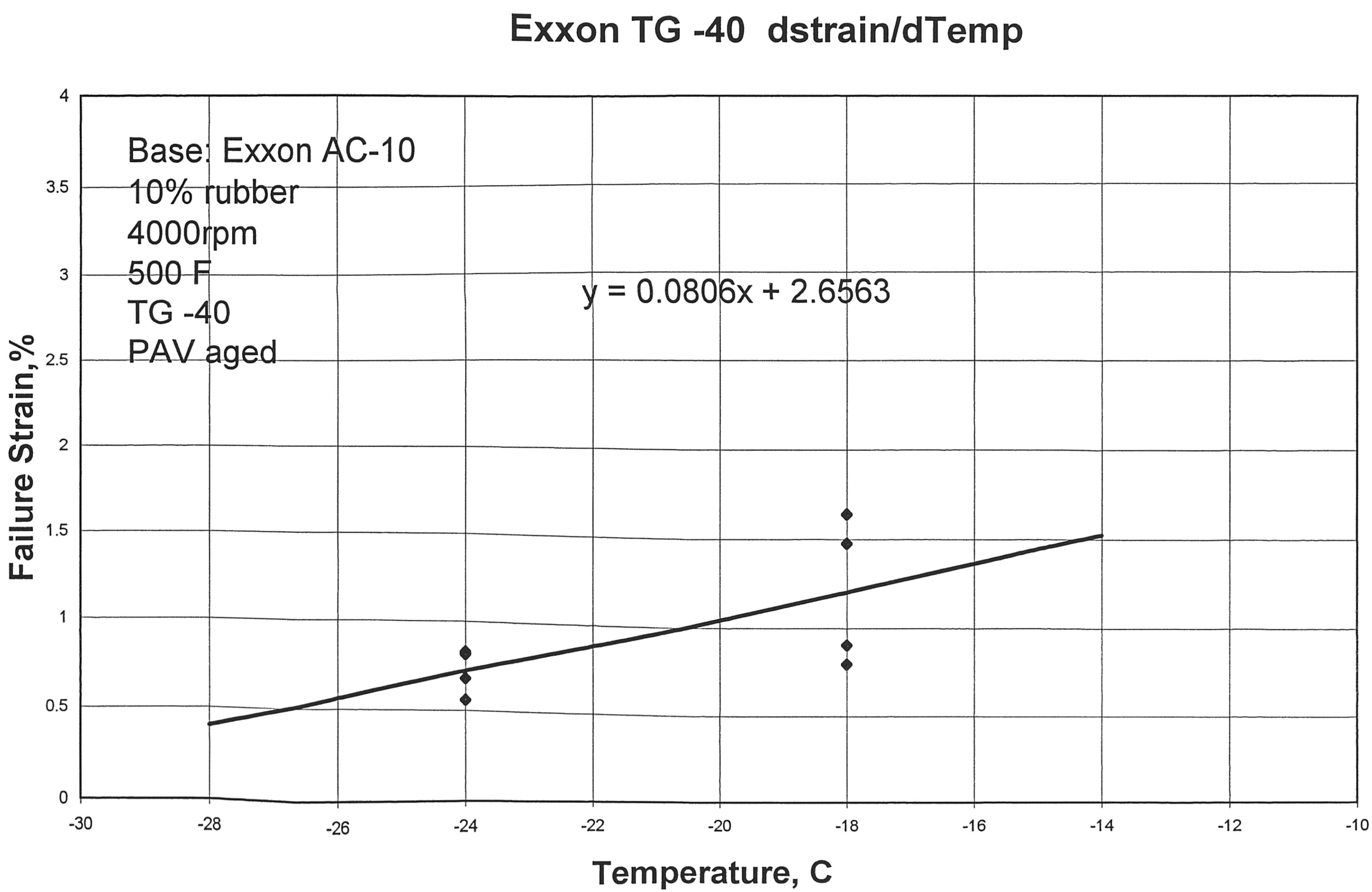


Exxon Standard d(f.stiffness)/dTemp
Base: Exxon AC-10
10% rubber
4000rpm
500 F
TG -10
PAV aged
y = -192.21x - 2439.9
Failure Stiffness, kg/cm^2
Temperature, C
3500
3000
2500
2000
1500
1000
500
0
-30
-28
-26
-24
-22
-20
-18
-16
-14
-12
-10

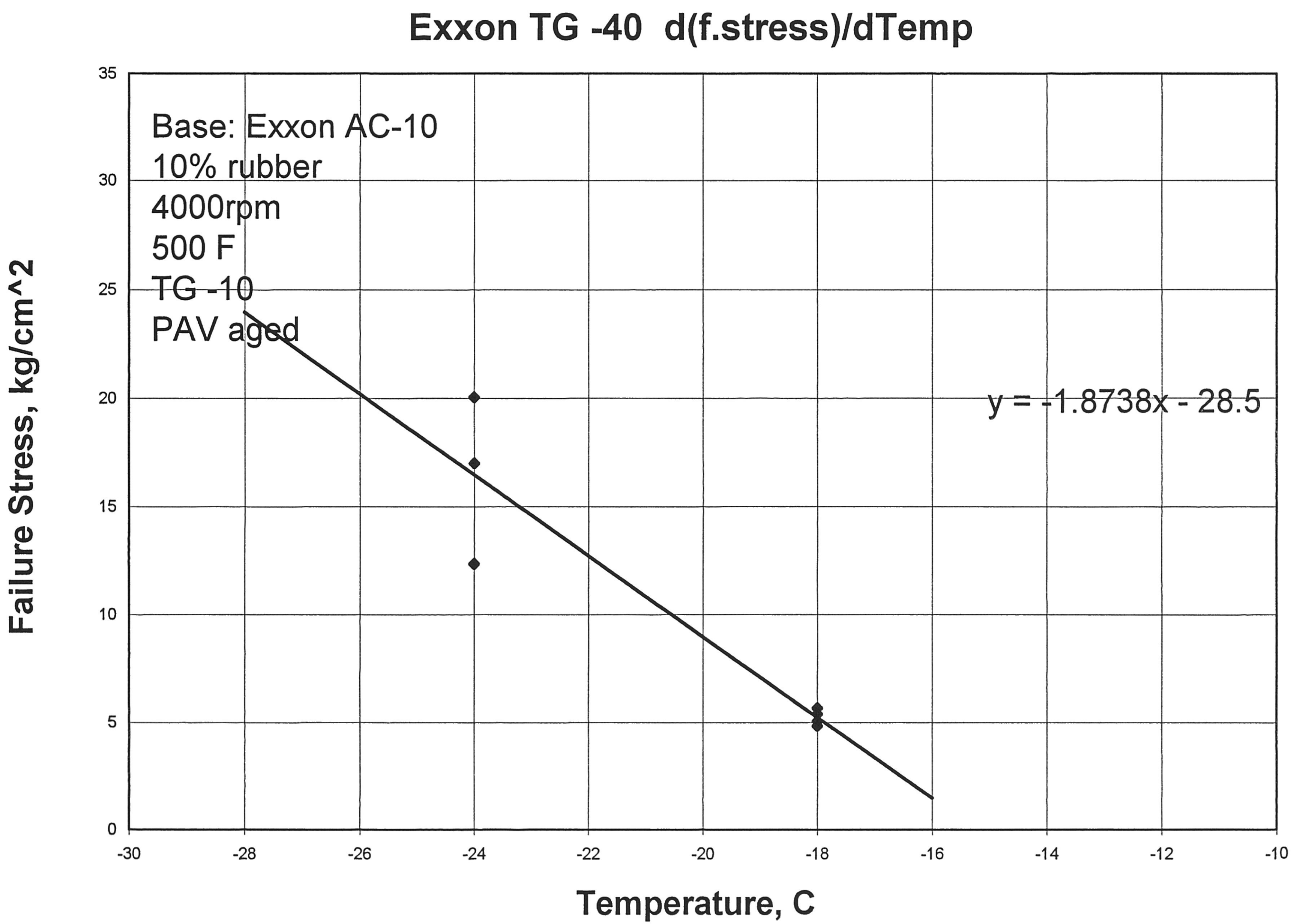

Exxon 8000rpm dstrain/dTemp
Base: Exxon AC-10
10% rubber
8000rpm
500 F
TG -10
PAV aged
y = 0.1146x + 3.7635
Failure Strain,%
4
3.5
3
2.5
2
1.5
1
0.5
0
-30
-28
-26
-24
-22
-20
-18
-16
-14
-12
-10
Temperature, C


Exxon 8000rpm d(f.stress)/dTemp
Base: Exxon AC-10
10% rubber
8000rpm
500 F
TG -10
PAV aged
y = 0.7466x + 31.982
Failure Stress, kg/cm^2
Temperature, C
35
30
25
20
15
10
5
0
-30
-28
-26
-24
-22
-20
-18
-16
-14
-12
-10

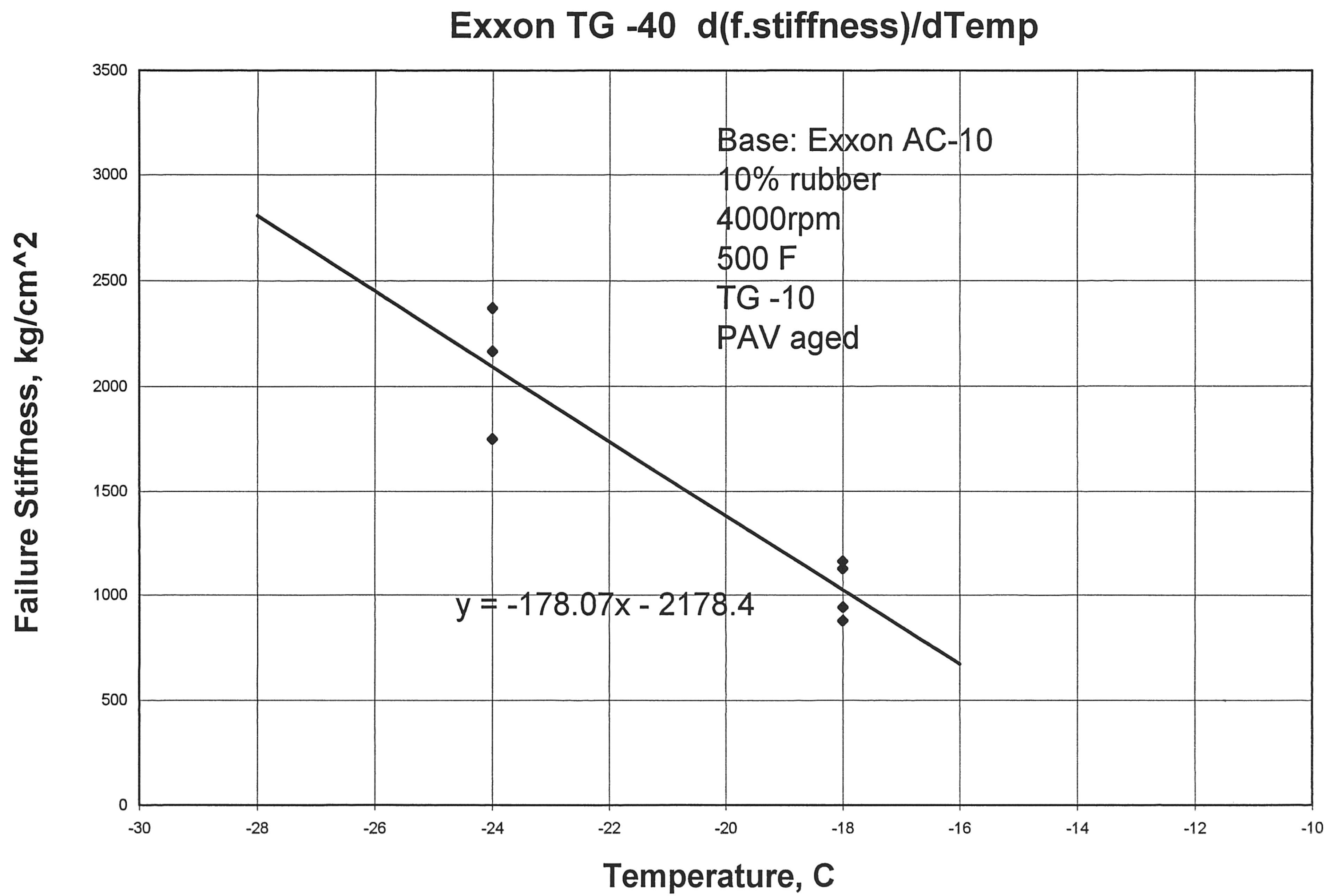

Exxon 8000rpm d(f.stiffness)/dTemp
Base: Exxon AC-10
10% rubber
8000rpm
500 F
TG -10
PAV aged
y = -103.22x - 797.39
Failure Stiffness, kg/cm^2
Temperature, C
3500
3000
2500
2000
1500
1000
500
0
-30
-28
-26
-24
-22
-20
-18
-16
-14
-12
-10

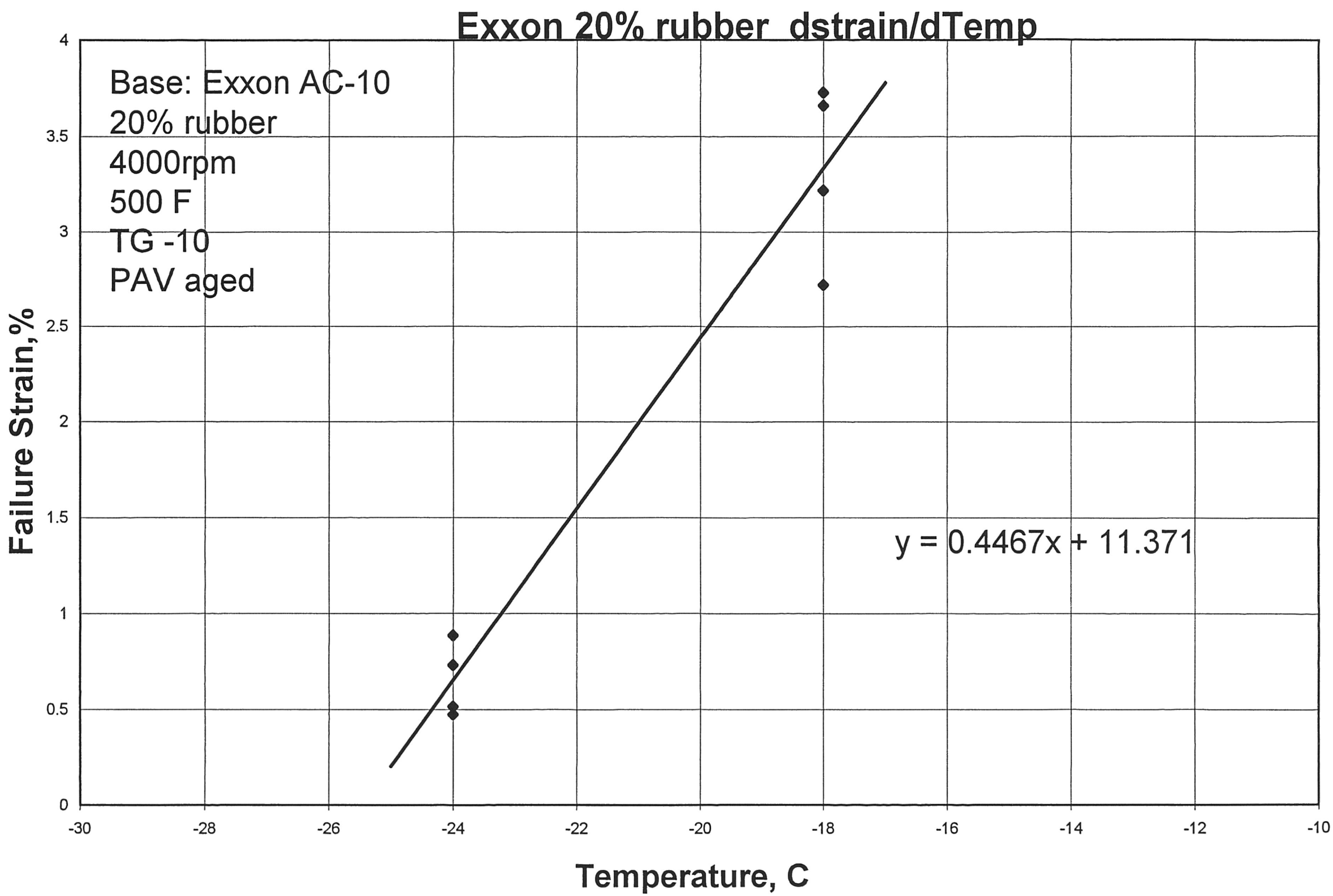


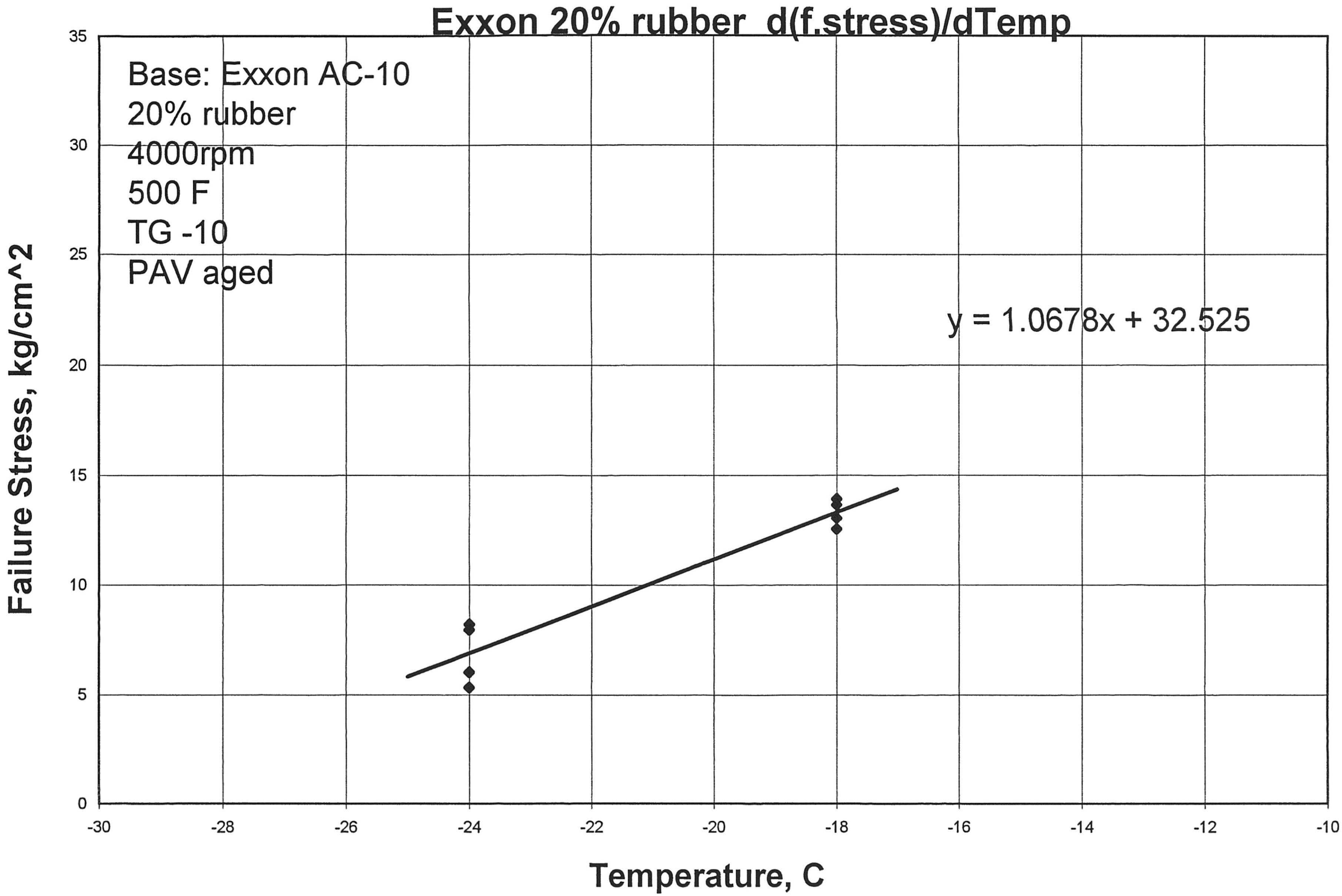
Exxon TG -40 dstrain/dTemp
Base: Exxon AC-10
10% rubber
4000rpm
500 F
TG -40
PAV aged
y = 0.0806x + 2.6563
Failure Strain,%
Temperature, C
4
3.5
3
2.5
2
1.5
1
0.5
0
-30
-28
-26
-24
-22
-20
-18
-16
-14
-12
-10

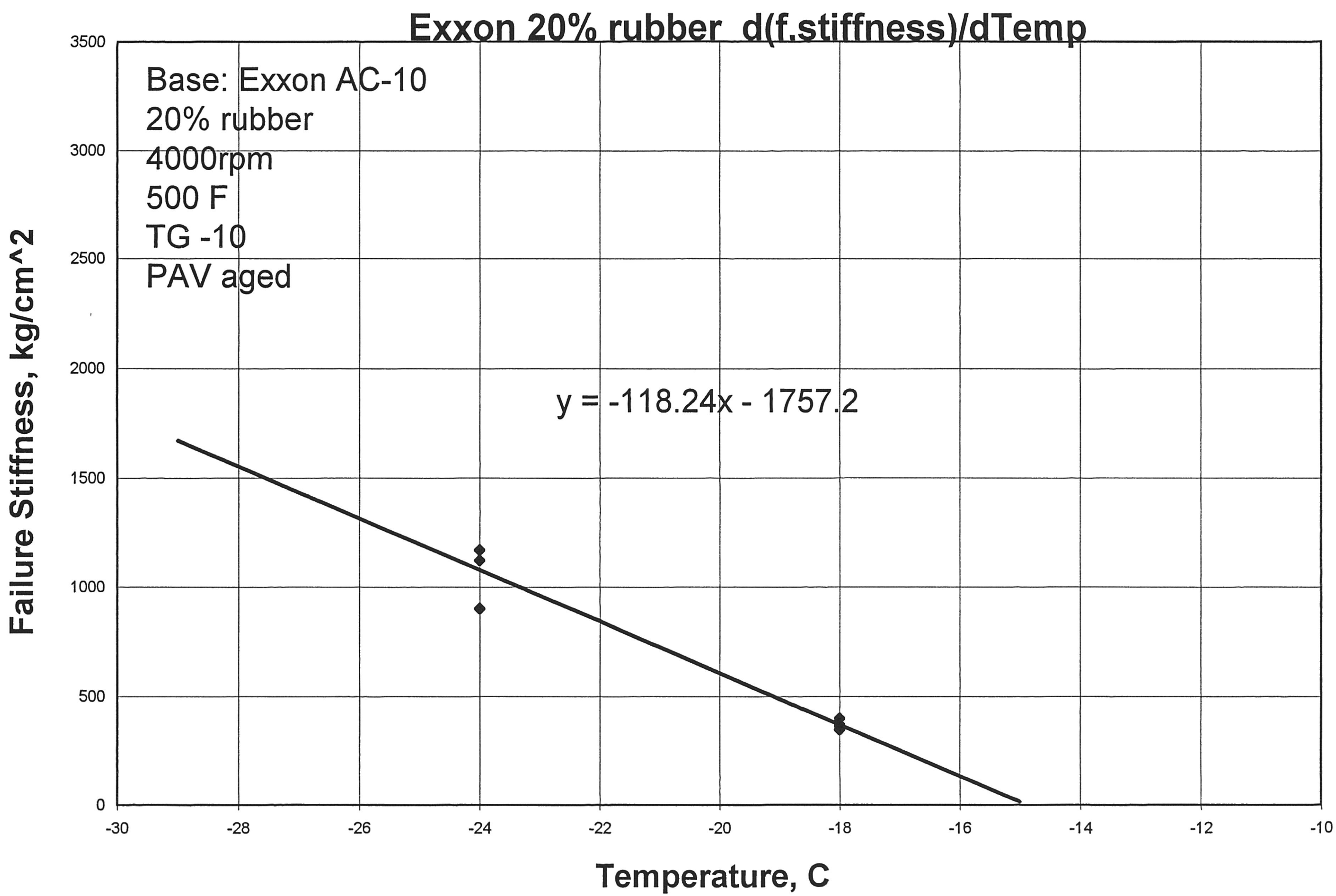


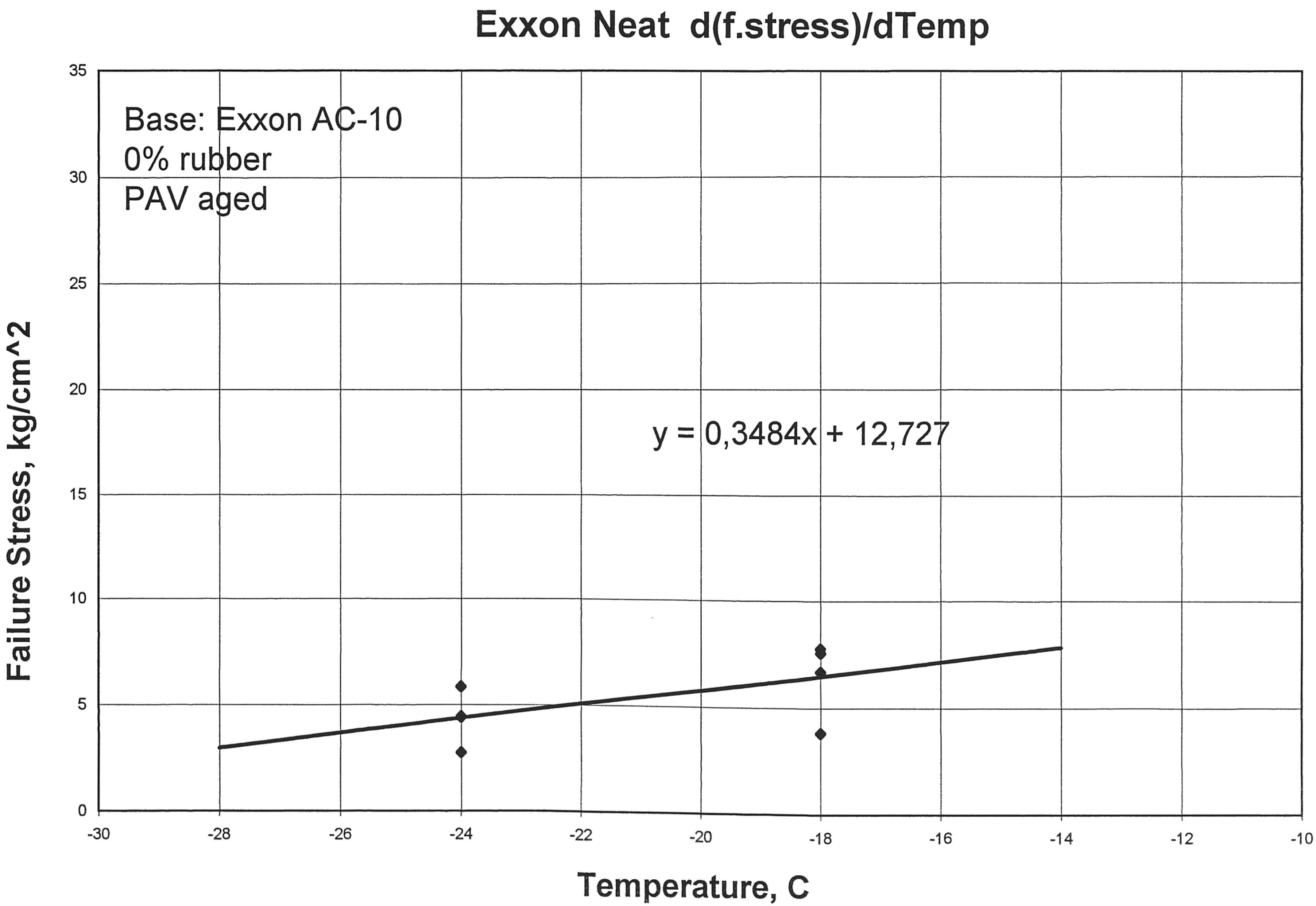
Exxon TG -40 d(f.stress)/dTemp
Base: Exxon AC-10
10% rubber
4000rpm
500 F
TG -10
PAV aged
y = -1.8738x - 28.5
Failure Stress, kg/cm^2
Temperature, C
35
30
25
20
15
10
5
0
-30
-28
-26
-24
-22
-20
-18
-16
-14
-12
-10

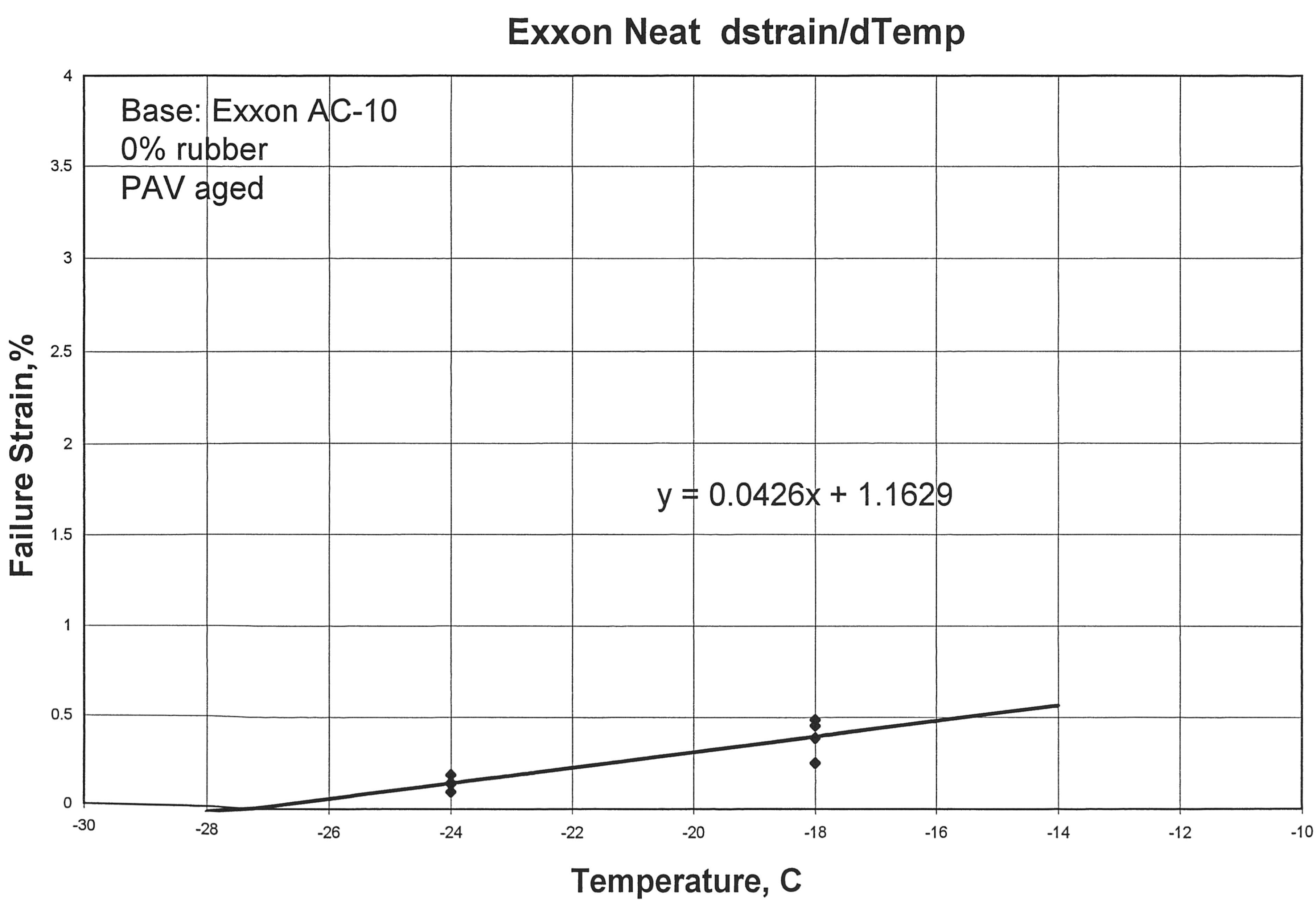

Exxon TG -40 d(f.stiffness)/dTemp
Base: Exxon AC-10
10% rubber
4000rpm
500 F
TG -10
PAV aged
y = -178.07x - 2178.4
Failure Stiffness, kg/cm^2
Temperature, C
3500
3000
2500
2000
1500
1000
500
0
-30
-28
-26
-24
-22
-20
-18
-16
-14
-12
-10


Exxon 20% rubber dstrain/dTemp
Base: Exxon AC-10
20% rubber
4000rpm
500 F
TG -10
PAV aged
y = 0.4467x + 11.371
Failure Strain,%
Temperature, C
0
0.5
1
1.5
2
2.5
3
3.5
4
-30
-28
-26
-24
-22
-20
-18
-16
-14
-12
-10

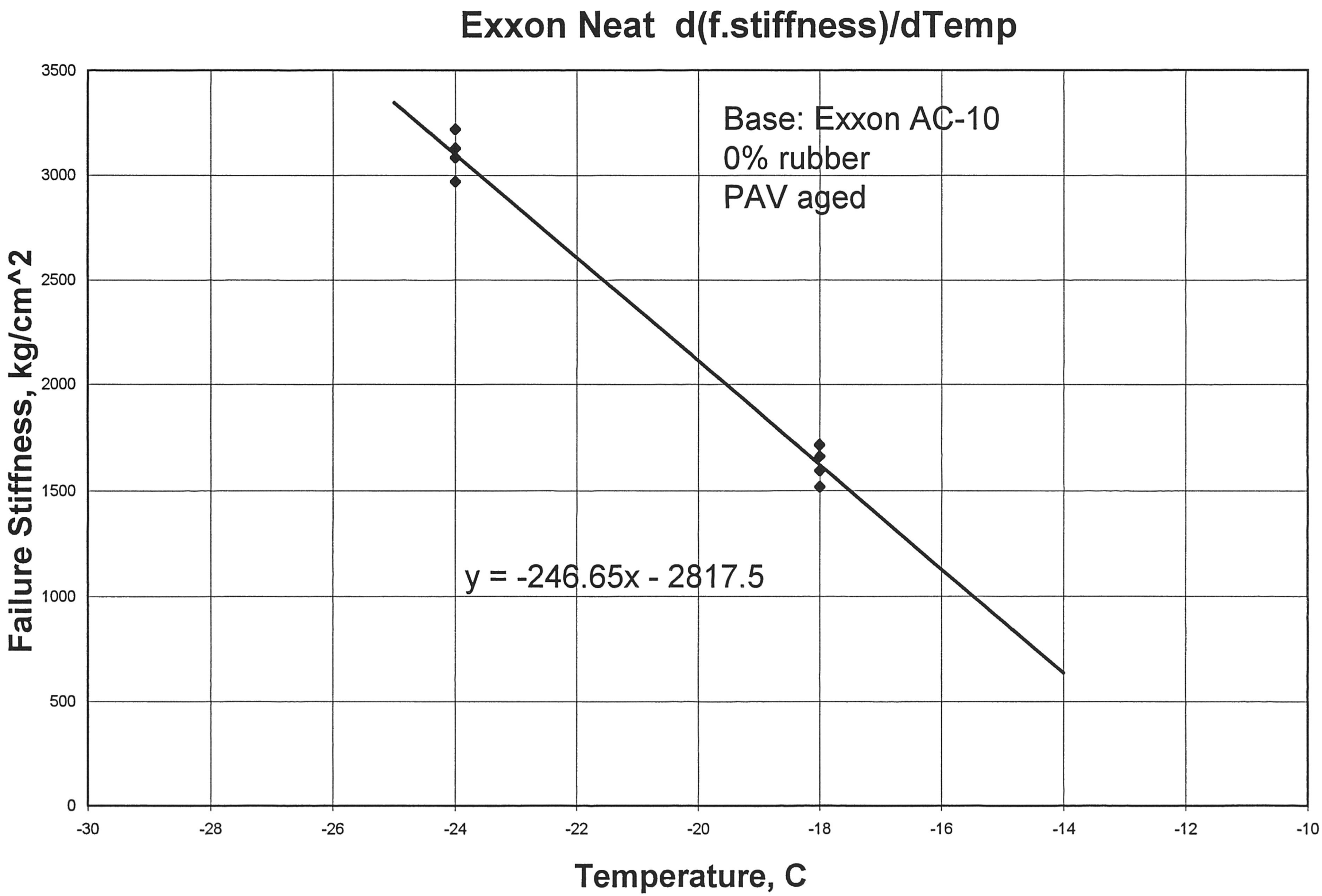

Exxon 20% rubber d(f.stress)/dTemp
Base: Exxon AC-10
20% rubber
4000rpm
500 F
TG -10
PAV aged
y = 1.0678x + 32.525
Failure Stress, kg/cm^2
35
30
25
20
15
10
5
0
-30
-28
-26
-24
-22
-20
-18
-16
-14
-12
-10
Temperature, C


Exxon 20% rubber d(f.stiffness)/dTemp
Base: Exxon AC-10
20% rubber
4000rpm
500 F
TG -10
PAV aged
y = -118.24x - 1757.2
Failure Stiffness, kg/cm^2
Temperature, C
3500
3000
2500
2000
1500
1000
500
0
-30
-28
-26
-24
-22
-20
-18
-16
-14
-12
-10

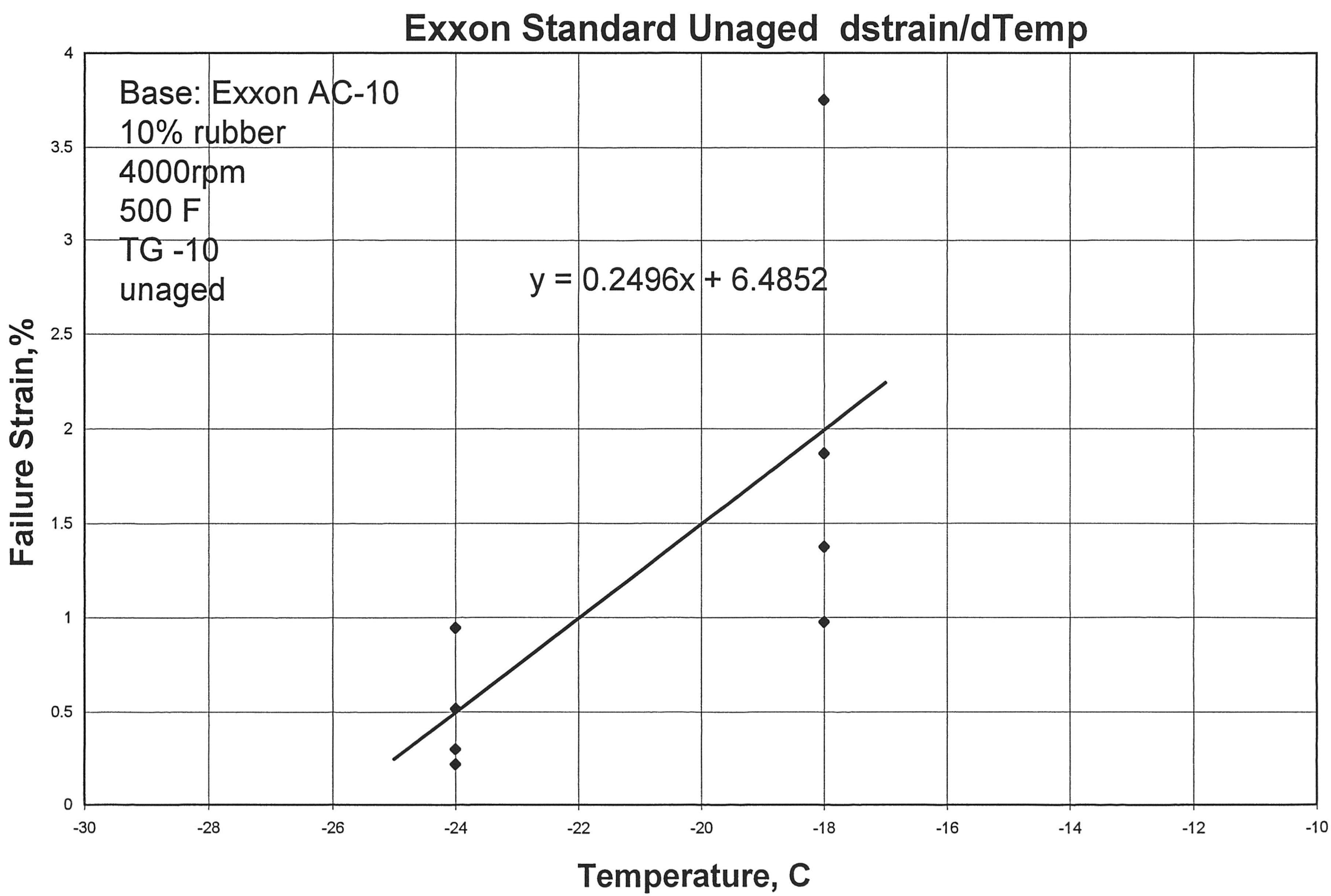

Exxon Neat d(f.stress)/dTemp
Base: Exxon AC-10
0% rubber
PAV aged
y = 0,3484x + 12,727
Failure Stress, kg/cm^2
Temperature, C
35
30
25
20
15
10
5
0
-30
-28
-26
-24
-22
-20
-18
-16
-14
-12
-10



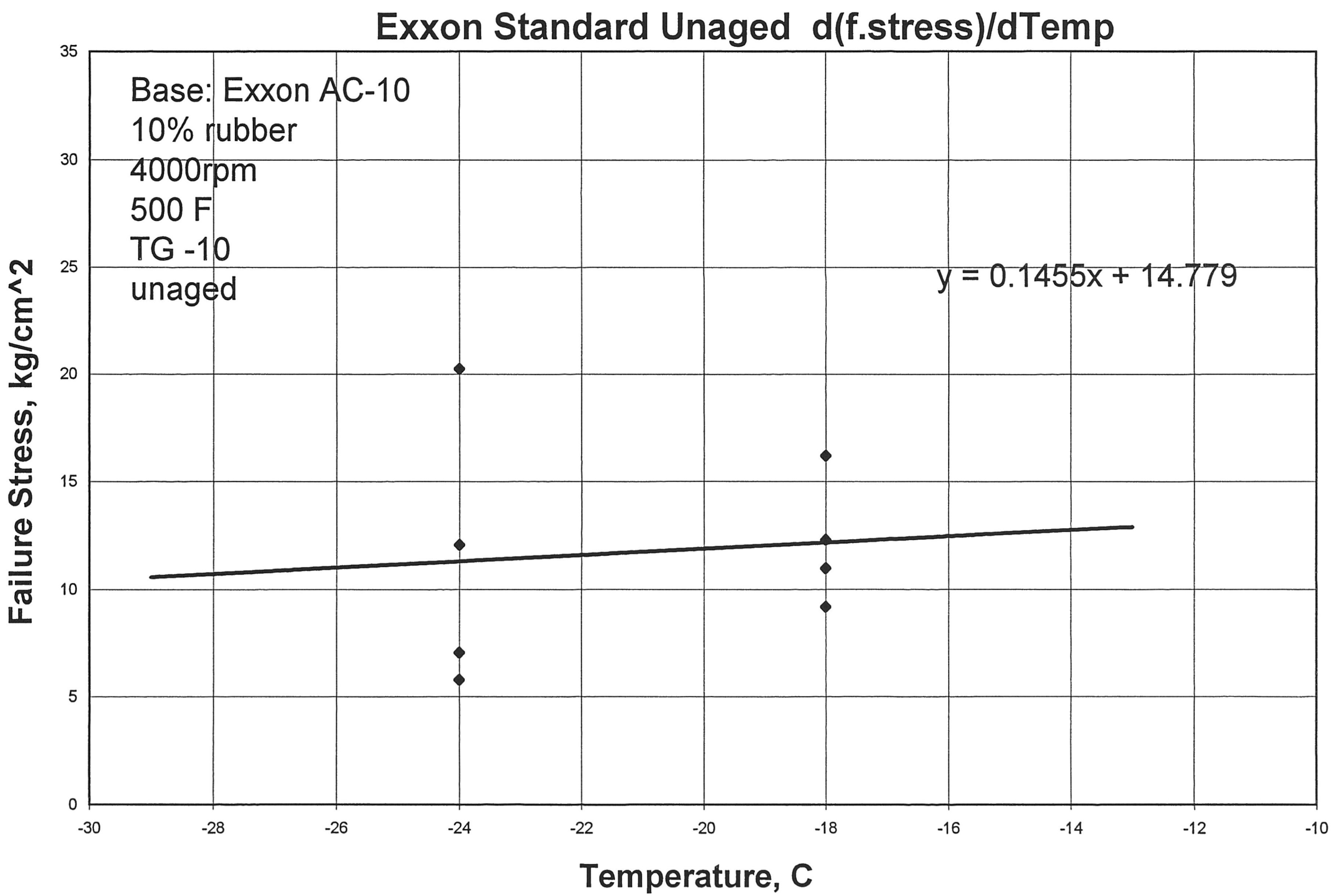
Exxon Neat dstrain/dTemp
Base: Exxon AC-10
0% rubber
PAV aged
y = 0.0426x + 1.1629
Failure Strain,%
Temperature, C
4
3.5
3
2.5
2
1.5
1
0.5
0
-30
-28
-26
-24
-22
-20
-18
-16
-14
-12
-10

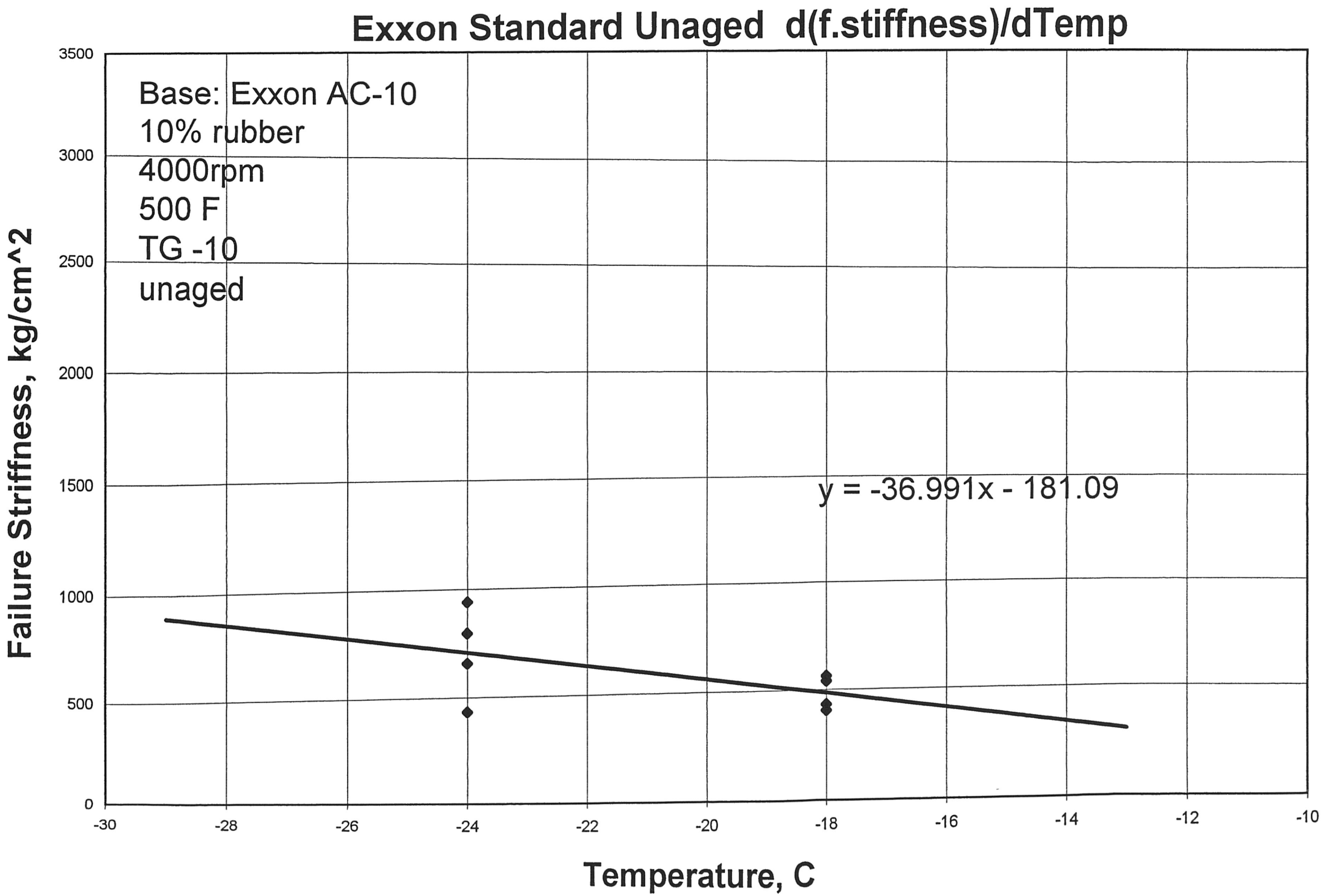


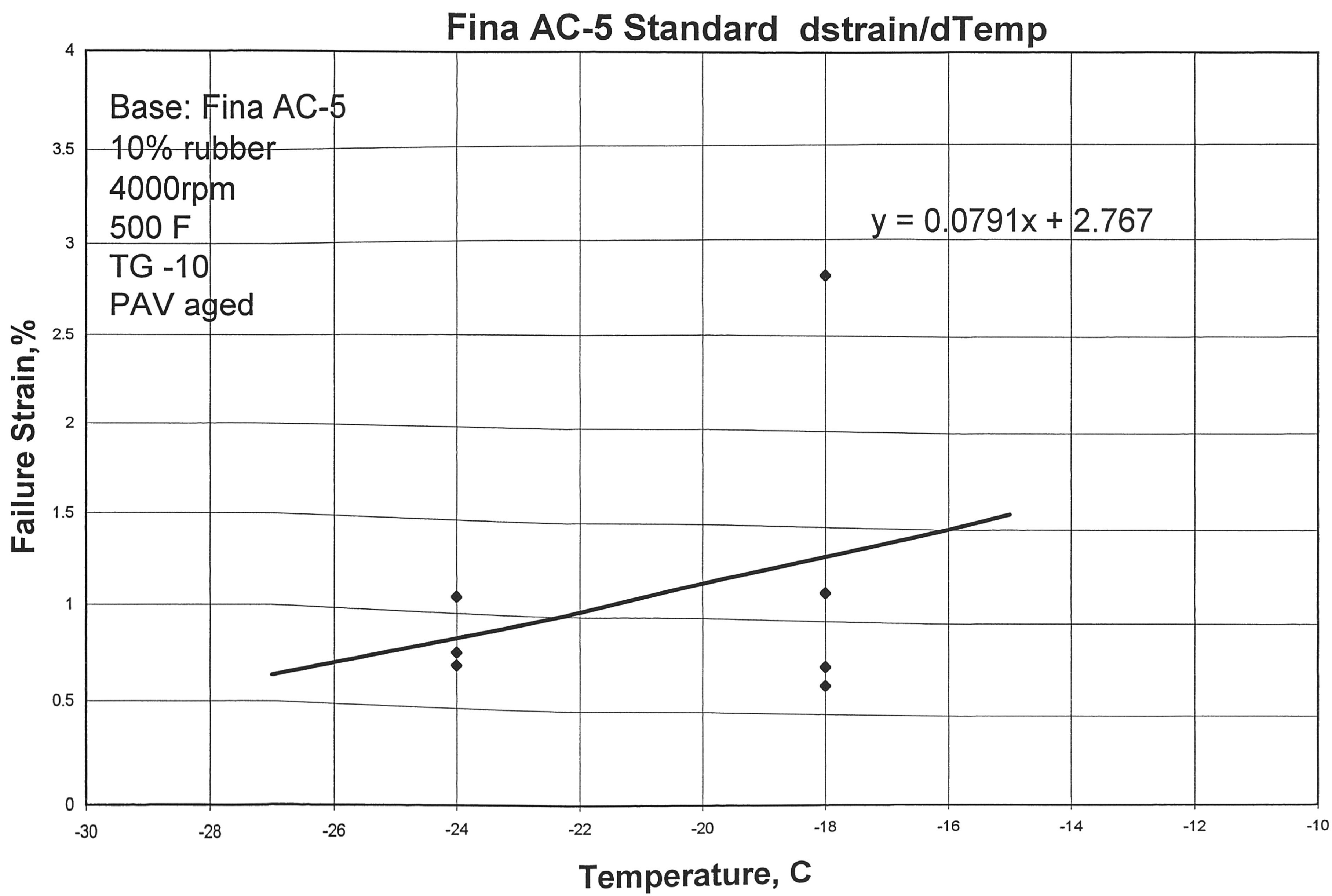
Exxon Neat d(f.stiffness)/dTemp
Base: Exxon AC-10
0% rubber
PAV aged
y = -246.65x - 2817.5
Failure Stiffness, kg/cm^2
Temperature, C
3500
3000
2500
2000
1500
1000
500
0
-30
-28
-26
-24
-22
-20
-18
-16
-14
-12
-10

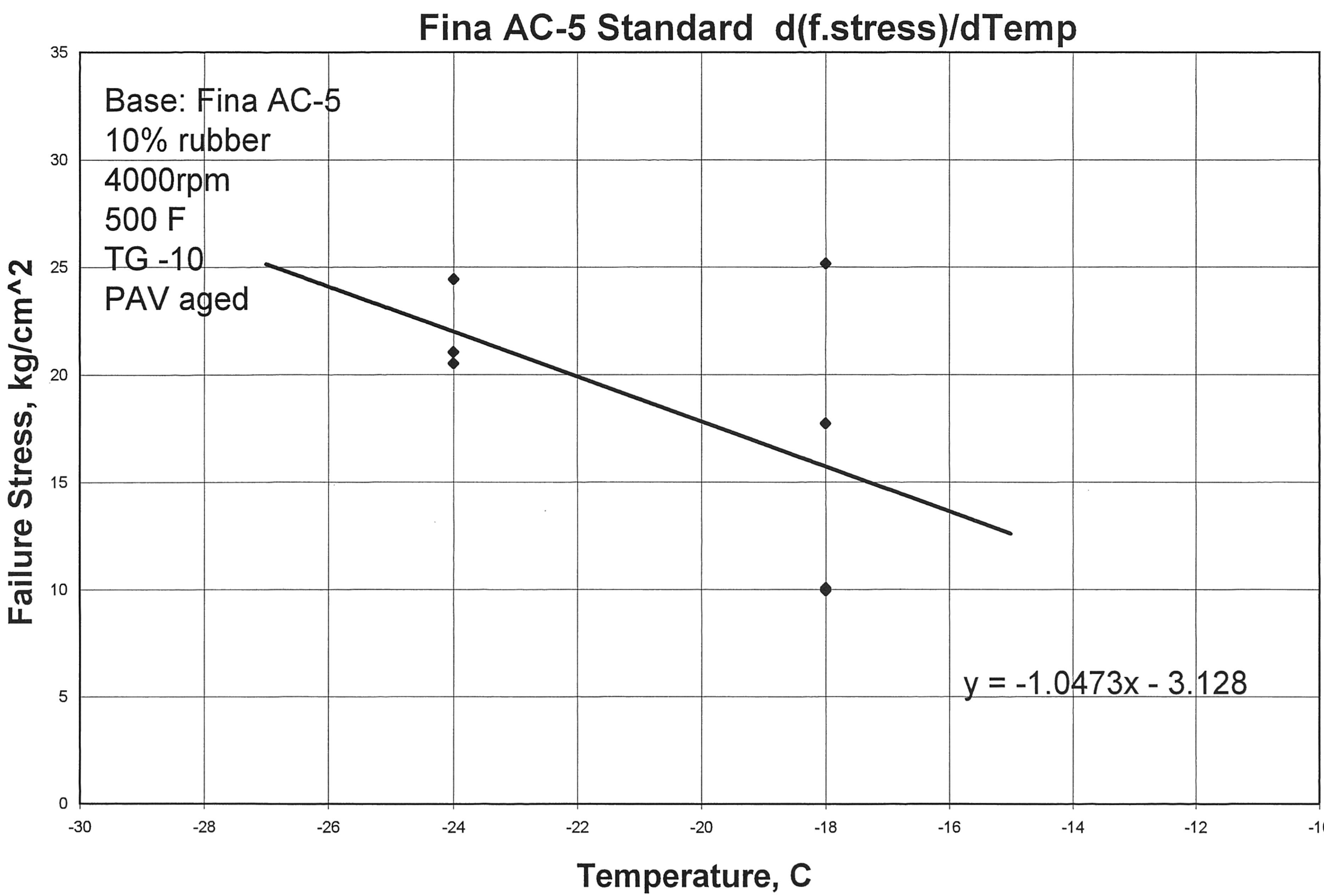


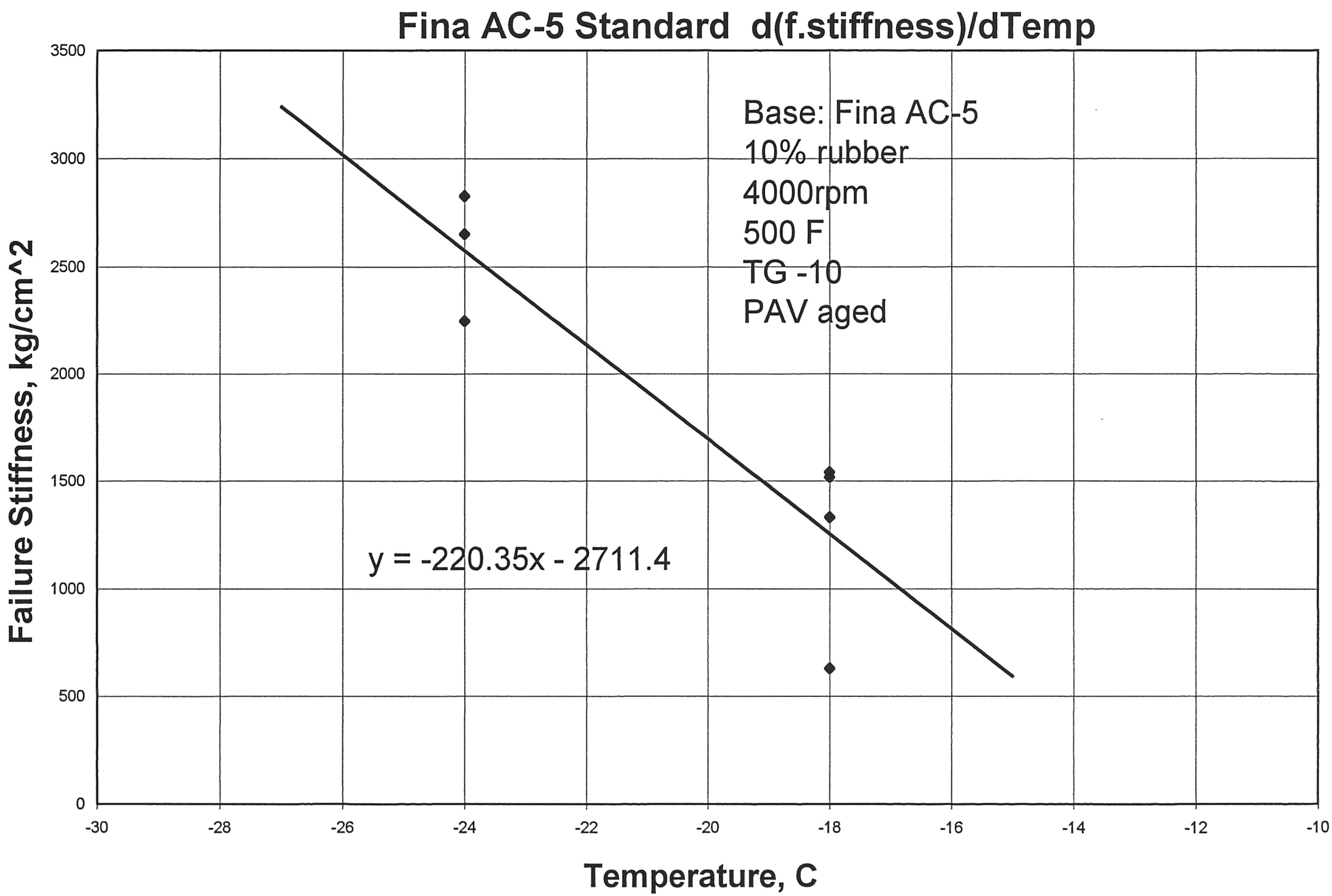
Exxon Standard Unaged dstrain/dTemp
Base: Exxon AC-10
10% rubber
4000rpm
500 F
TG -10
unaged
y = 0.2496x + 6.4852
Failure Strain,%
4
3.5
3
2.5
2
1.5
1
0.5
0
-30
-28
-26
-24
-22
-20
-18
-16
-14
-12
-10
Temperature, C

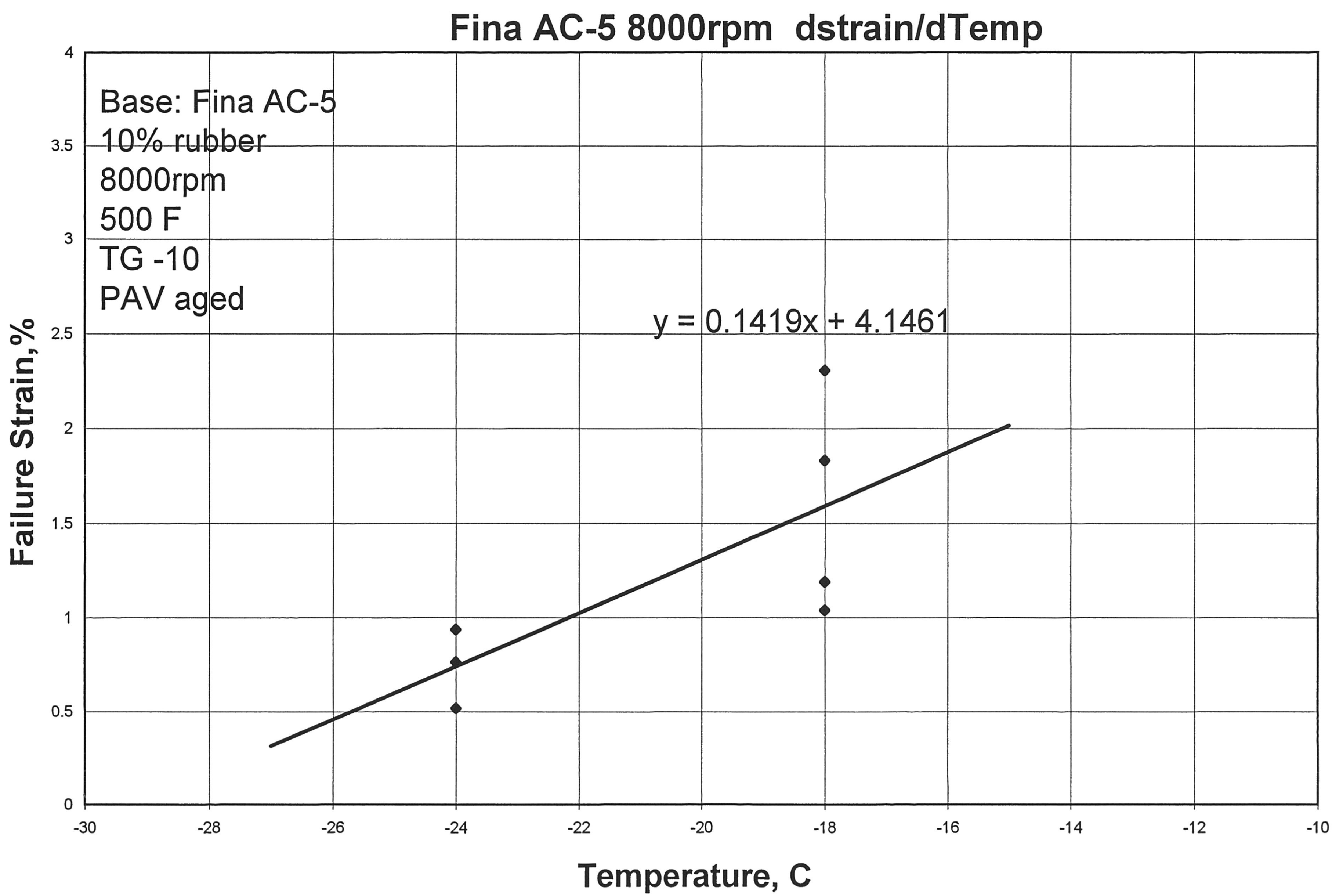

Exxon Standard Unaged d(f.stress)/dTemp
Base: Exxon AC-10
10% rubber
4000rpm
500 F
TG -10
unaged
y = 0.1455x + 14.779
Failure Stress, kg/cm^2
Temperature, C
35
30
25
20
15
10
5
0
-30
-28
-26
-24
-22
-20
-18
-16
-14
-12
-10


Exxon Standard Unaged d(f.stiffness)/dTemp
Base: Exxon AC-10
10% rubber
4000rpm
500 F
TG -10
unaged
y = -36.991x - 181.09
Failure Striffness, kg/cm^2
3500
3000
2500
2000
1500
1000
500
0
-30
-28
-26
-24
-22
-20
-18
-16
-14
-12
-10
Temperature, C

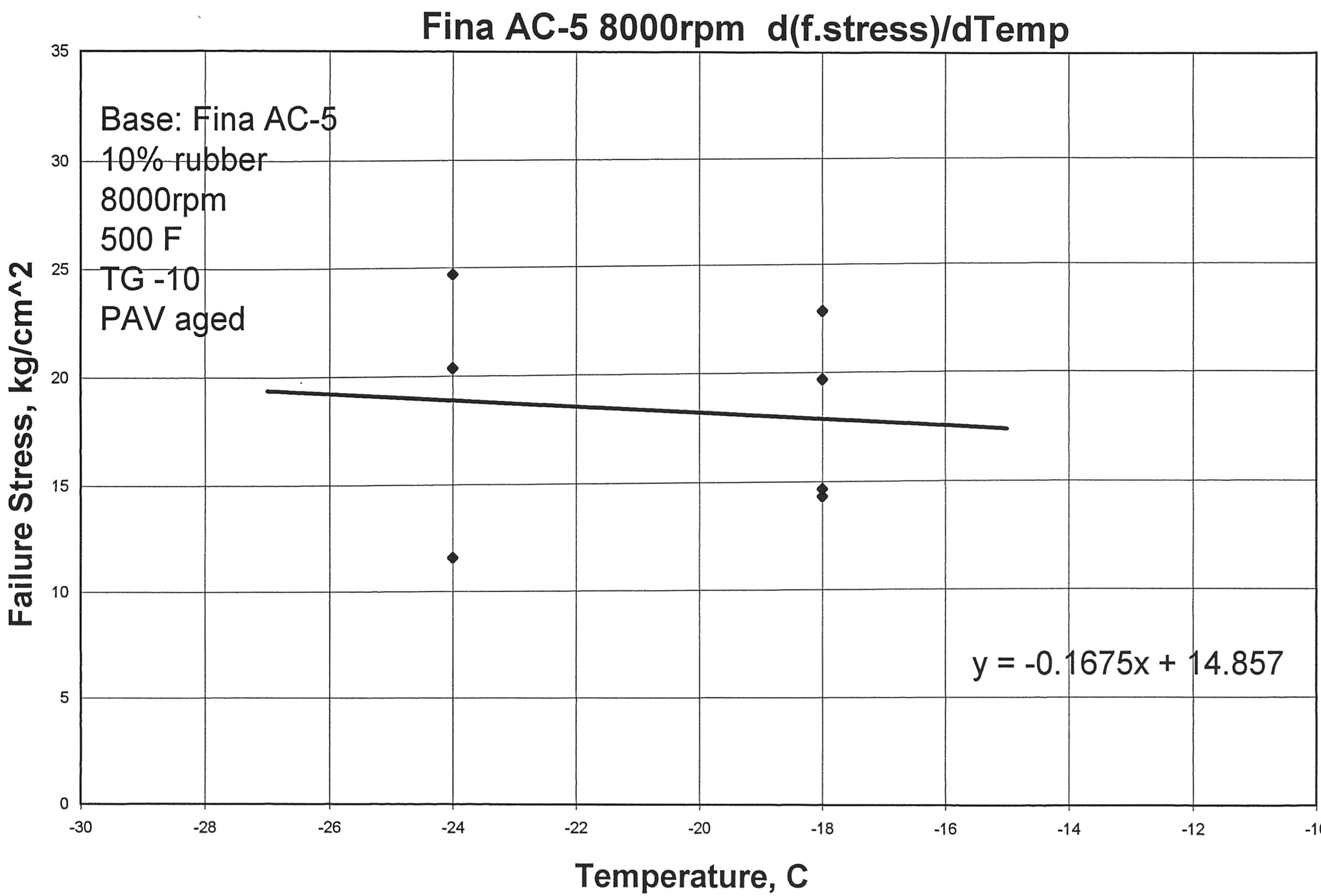

Fina AC-5 Standard dstrain/dTemp
Base: Fina AC-5
10% rubber
4000rpm
500 F
TG -10
PAV aged
y = 0.0791x + 2.767
Failure Strain,%
Temperature, C
4
3.5
3
2.5
2
1.5
1
0.5
0
-30
-28
-26
-24
-22
-20
-18
-16
-14
-12
-10


Fina AC-5 Standard d(f.stress)/dTemp
Base: Fina AC-5
10% rubber
4000rpm
500 F
TG -10
PAV aged
y = -1.0473x - 3.128
Failure Stress, kg/cm^2
Temperature, C
35
30
25
20
15
10
5
0
-30
-28
-26
-24
-22
-20
-18
-16
-14
-12
-10

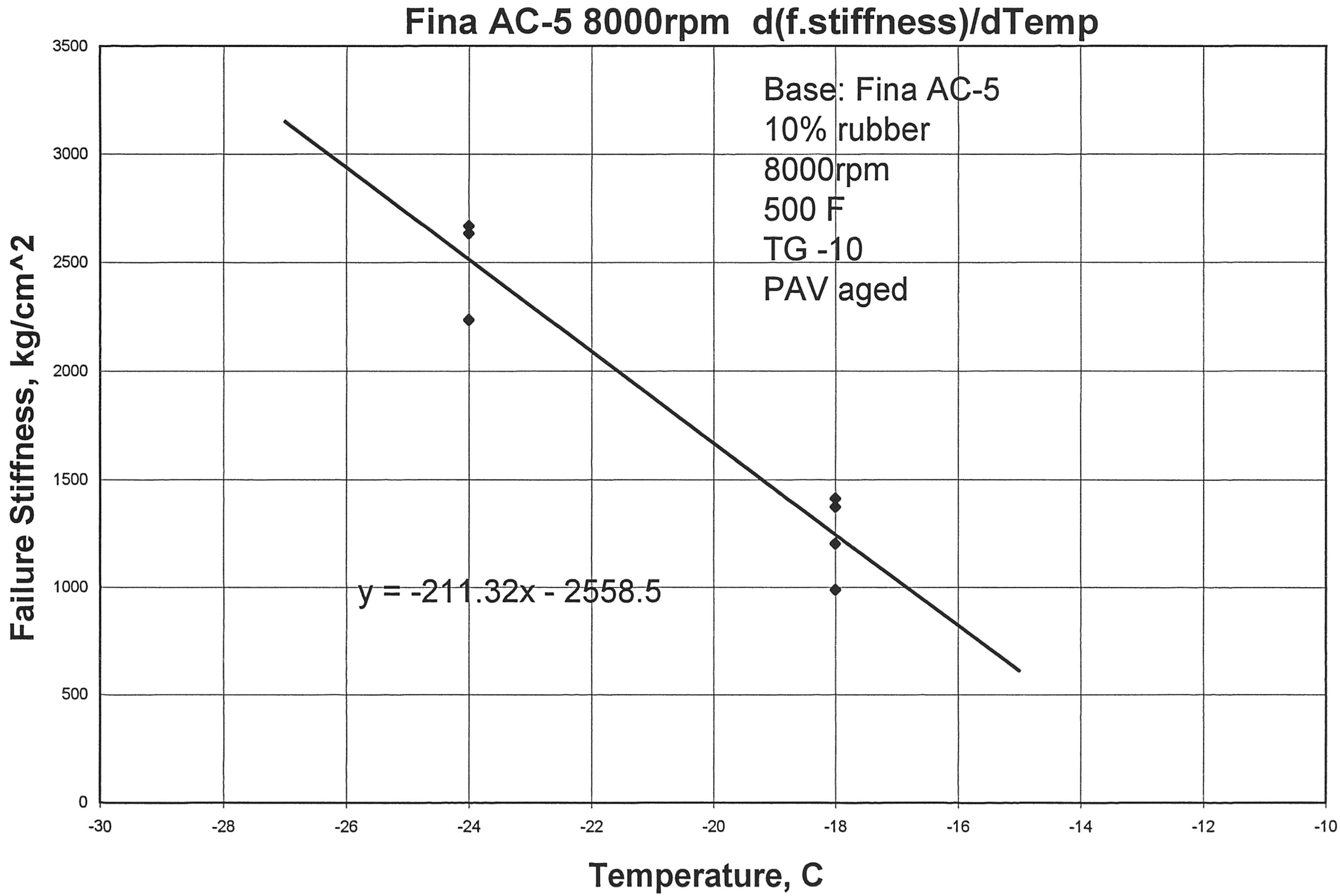

Fina AC-5 Standard d(f.stiffness)/dTemp
Base: Fina AC-5
10% rubber
4000rpm
500 F
TG -10
PAV aged
y = -220.35x - 2711.4
Failure Stiffness, kg/cm^2
Temperature, C
3500
3000
2500
2000
1500
1000
500
0
-30
-28
-26
-24
-22
-20
-18
-16
-14
-12
-10

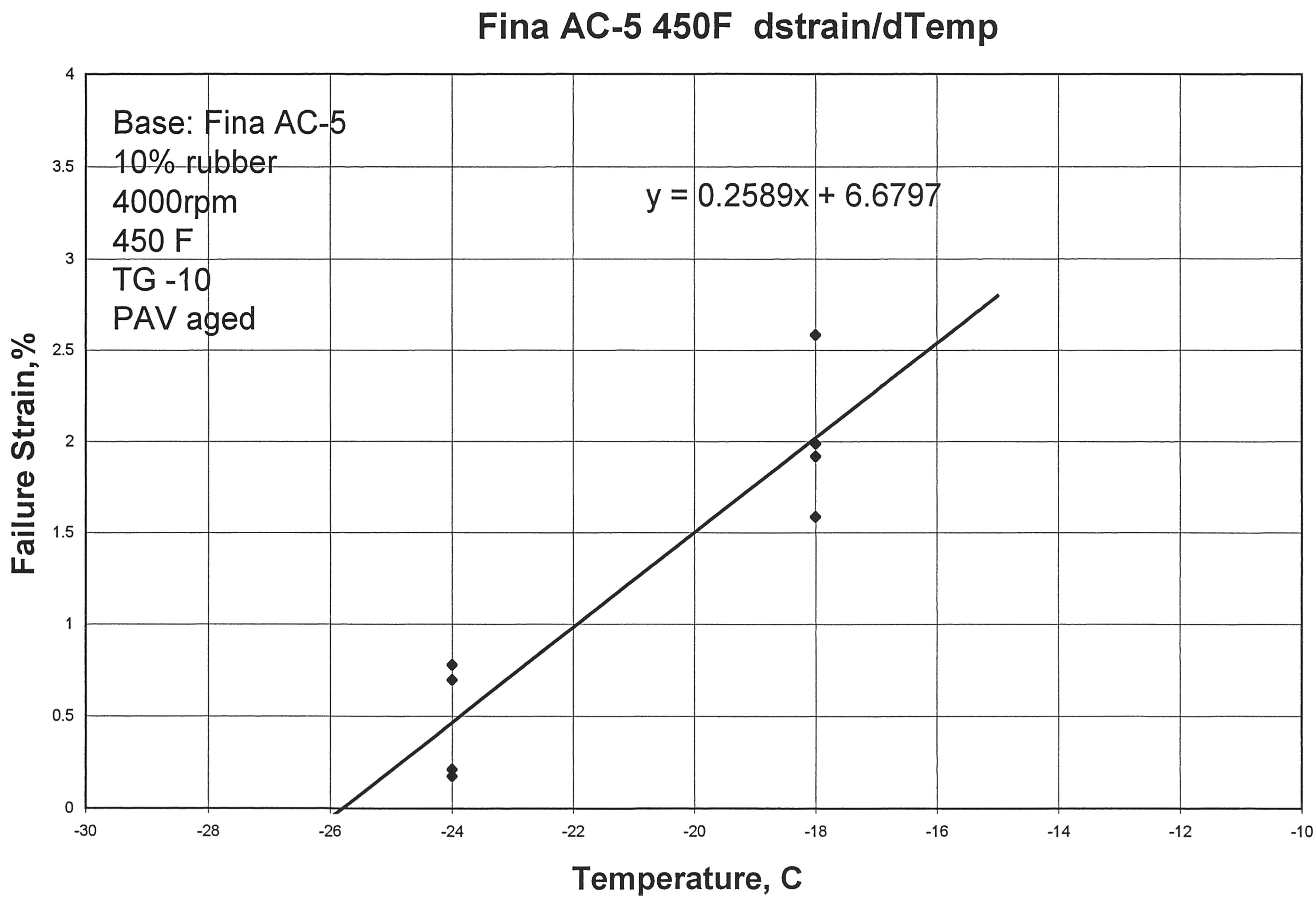


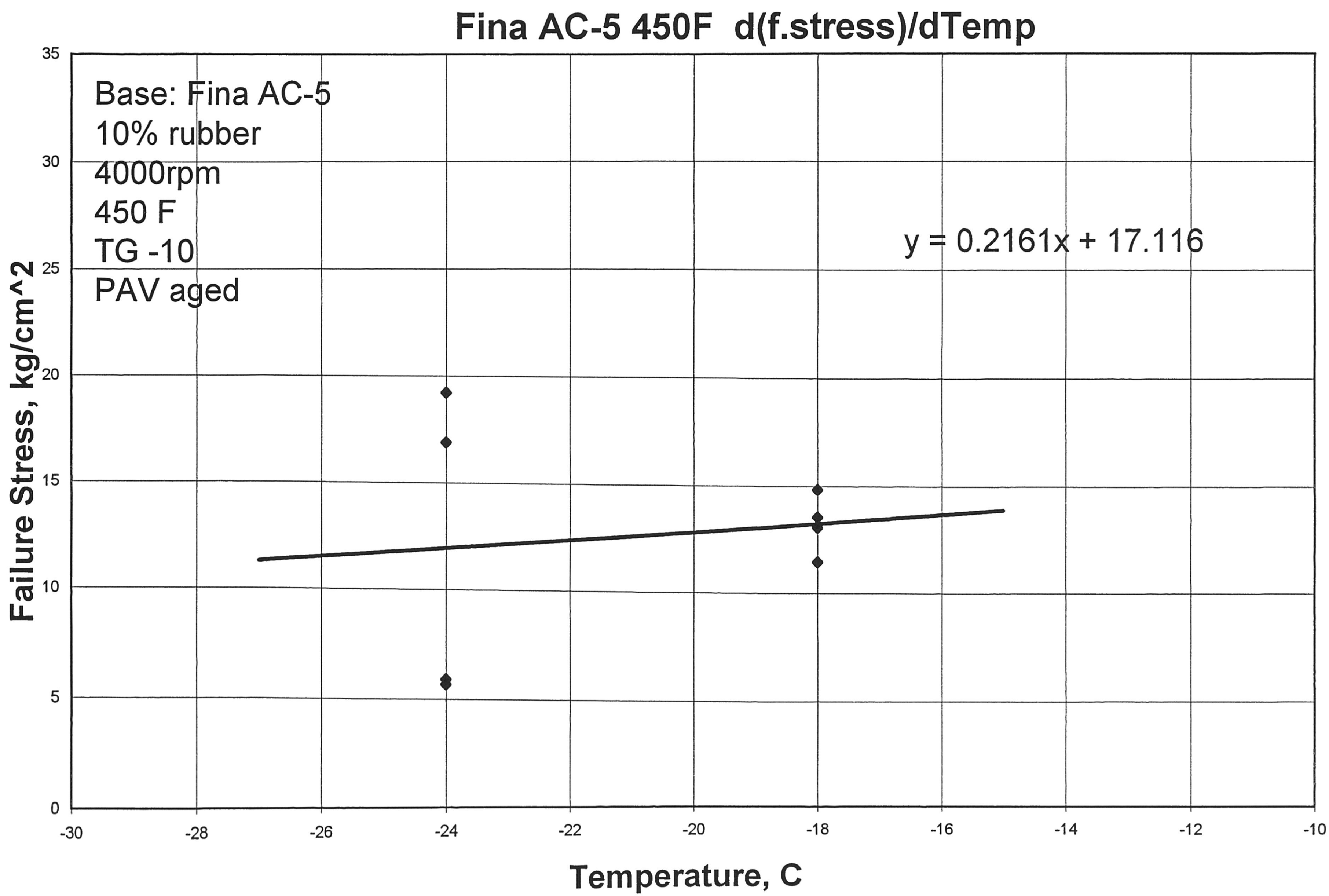
Fina AC-5 8000rpm dstrain/dTemp
Base: Fina AC-5
10% rubber
8000rpm
500 F
TG -10
PAV aged
y = 0.1419x + 4.1461
Failure Strain,%
4
3.5
3
2.5
2
1.5
1
0.5
0
-30
-28
-26
-24
-22
-20
-18
-16
-14
-12
-10
Temperature, C

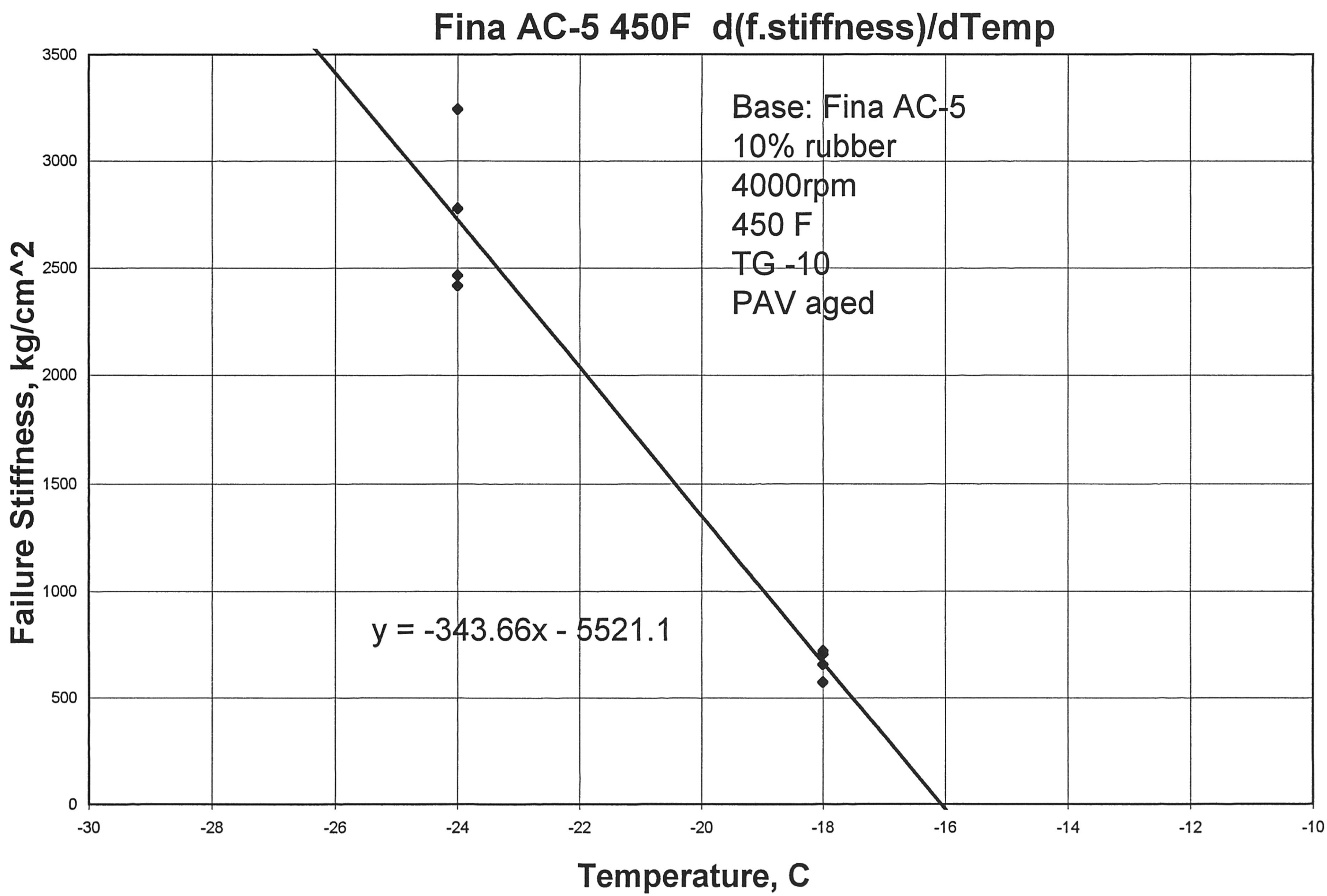


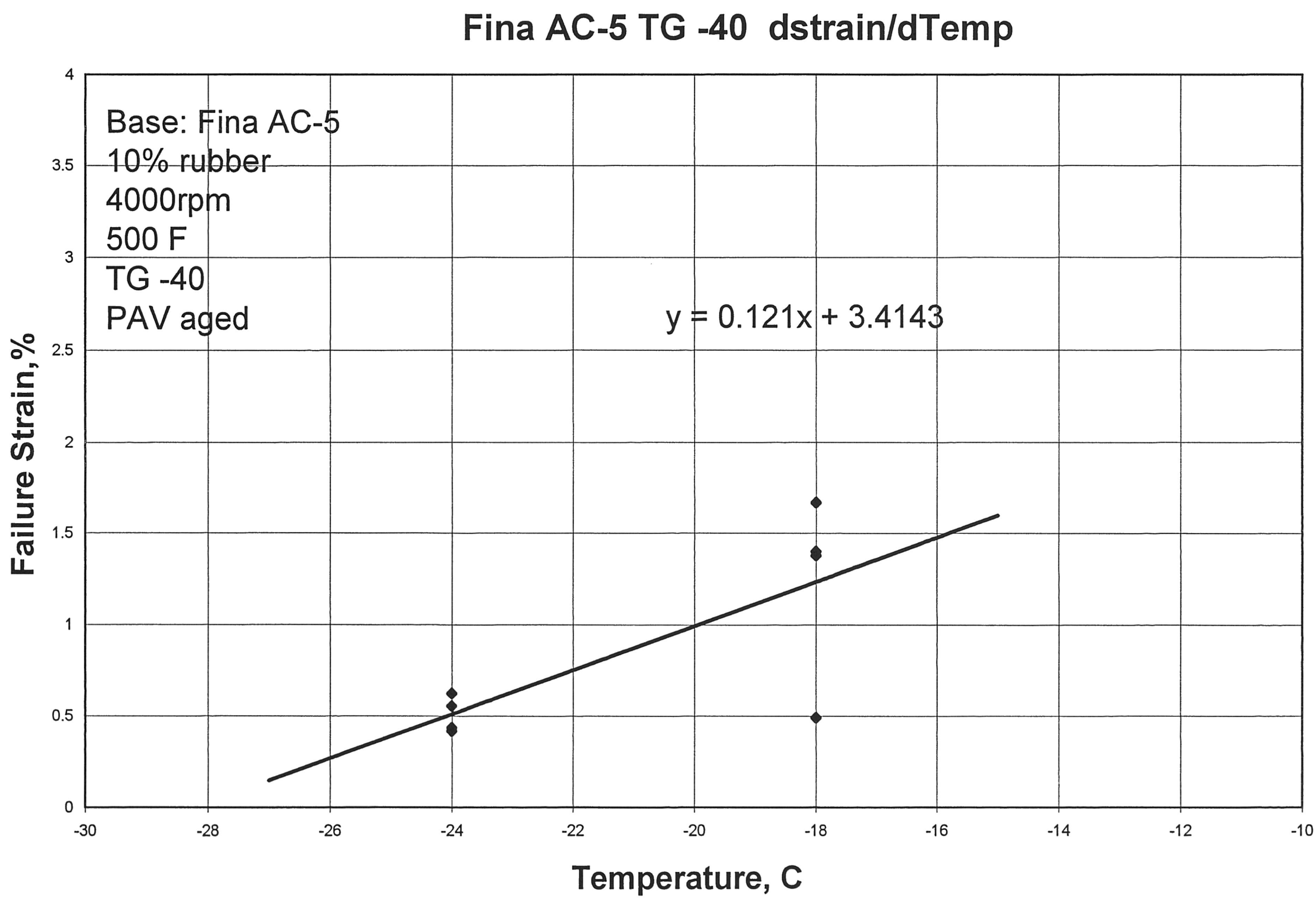
Fina AC-5 8000rpm d(f.stress)/dTemp
Base: Fina AC-5
10% rubber
8000rpm
500 F
TG -10
PAV aged
y = -0.1675x + 14.857
Failure Stress, kg/cm^2
Temperature, C
35
30
25
20
15
10
5
0
-30
-28
-26
-24
-22
-20
-18
-16
-14
-12
-10

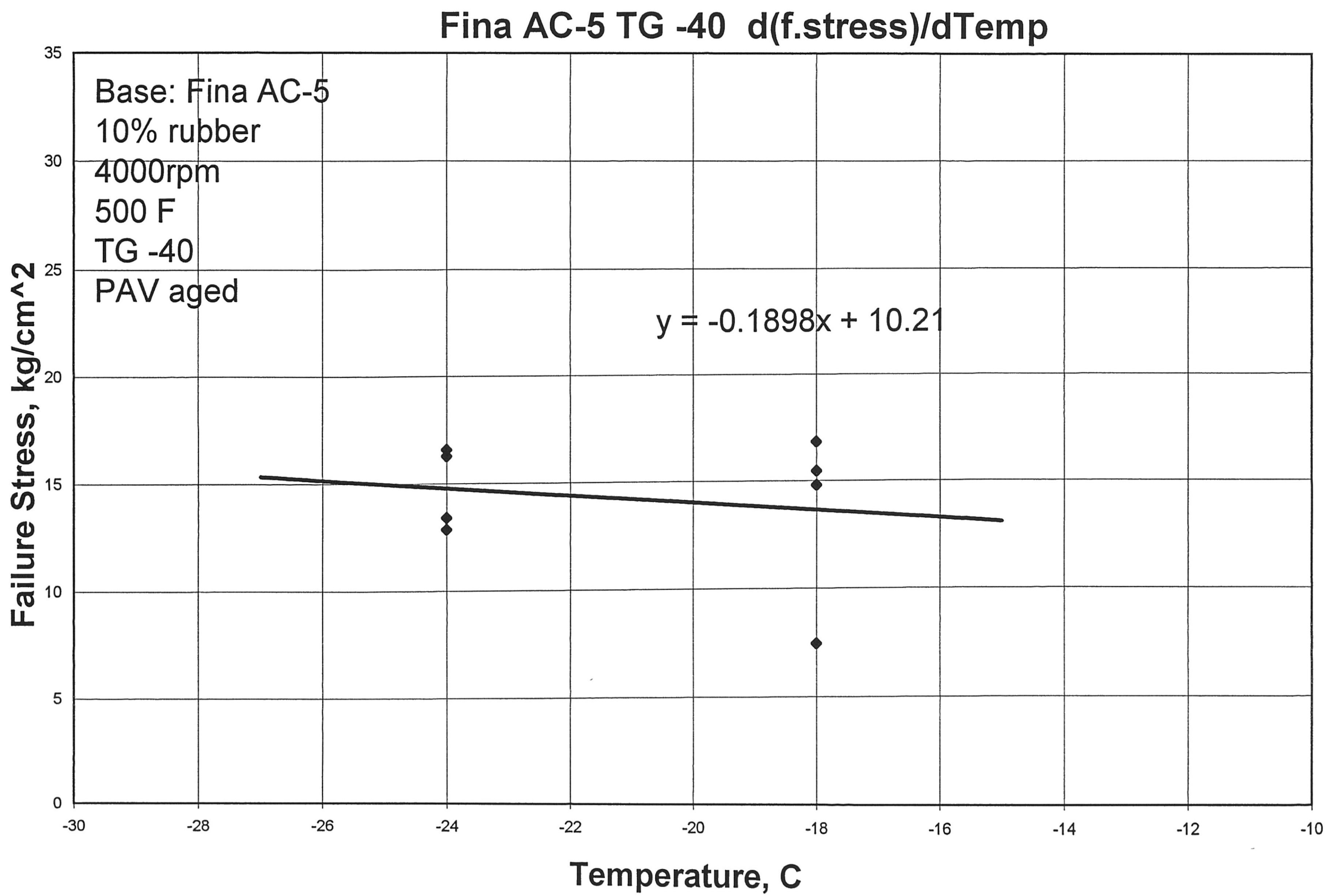

Fina AC-5 8000rpm d(f.stiffness)/dTemp
Base: Fina AC-5
10% rubber
8000rpm
500 F
TG -10
PAV aged
y = -211.32x - 2558.5
Failure Stiffness, kg/cm^2
Temperature, C
3500
3000
2500
2000
1500
1000
500
0
-30
-28
-26
-24
-22
-20
-18
-16
-14
-12
-10


Fina AC-5 450F dstrain/dTemp
Base: Fina AC-5
10% rubber
4000rpm
450 F
TG -10
PAV aged
y = 0.2589x + 6.6797
Failure Strain,%
4
3.5
3
2.5
2
1.5
1
0.5
0
-30
-28
-26
-24
-22
-20
-18
-16
-14
-12
-10
Temperature, C

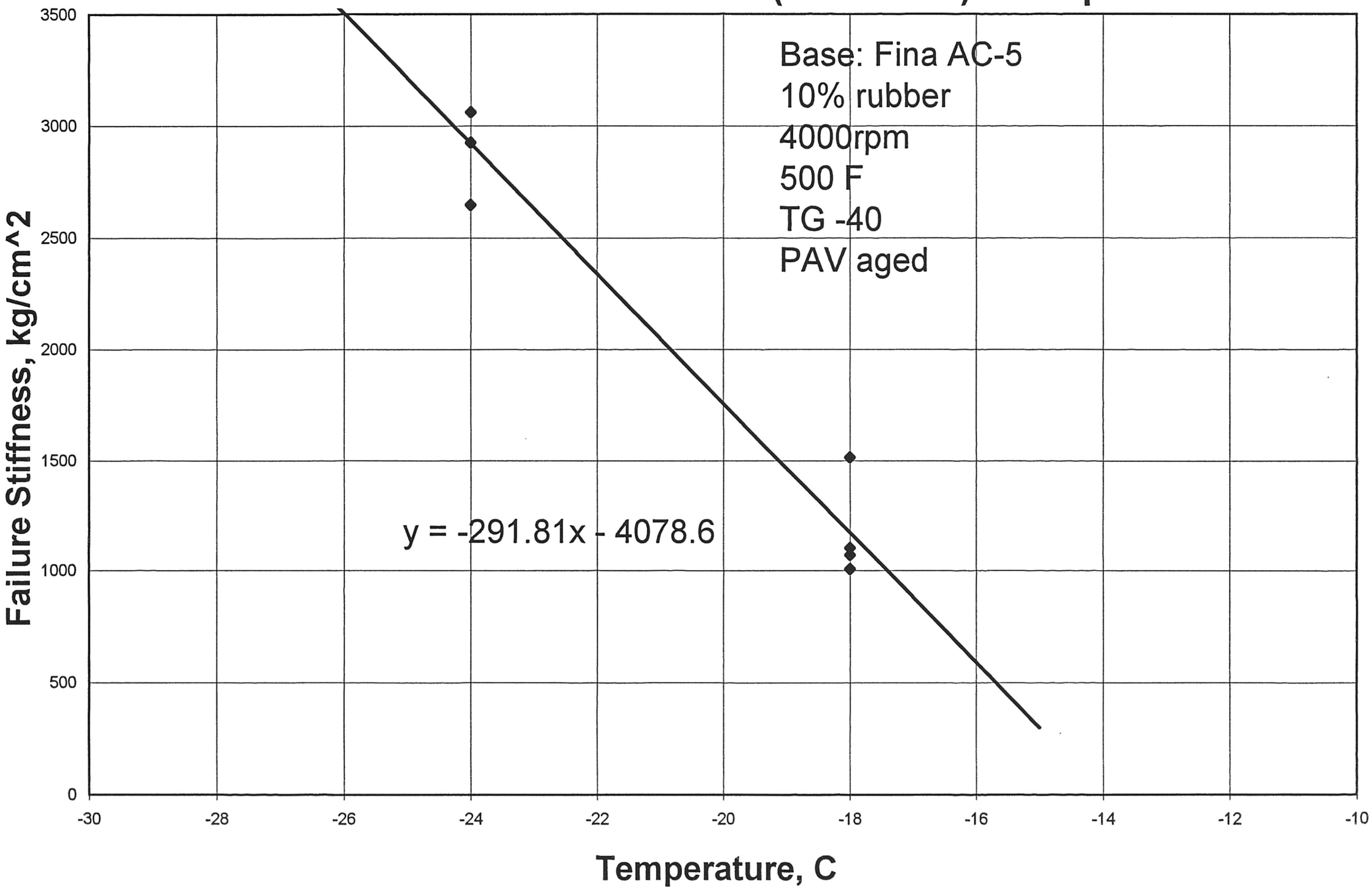

Fina AC-5 450F d(f.stress)/dTemp
Base: Fina AC-5
10% rubber
4000rpm
450 F
TG -10
PAV aged
y = 0.2161x + 17.116
Failure Stress, kg/cm^2
0
5
10
15
20
25
30
35
-30
-28
-26
-24
-22
-20
-18
-16
-14
-12
-10
Temperature, C

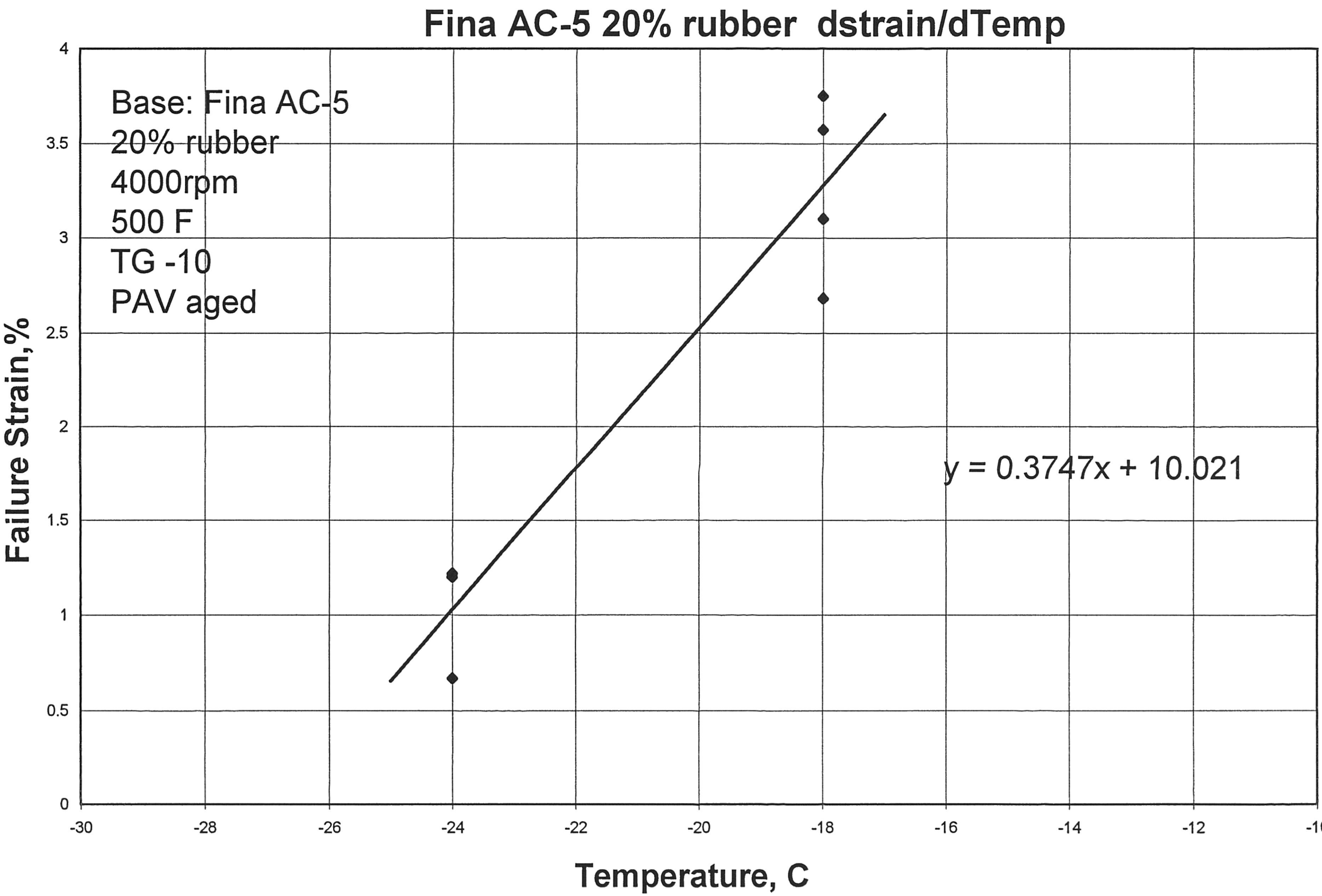

Fina AC-5 450F d(f.stiffness)/dTemp
Base: Fina AC-5
10% rubber
4000rpm
450 F
TG -10
PAV aged
y = -343.66x - 5521.1
Failure Stiffness, kg/cm^2
3500
3000
2500
2000
1500
1000
500
0
-30
-28
-26
-24
-22
-20
-18
-16
-14
-12
-10
Temperature, C

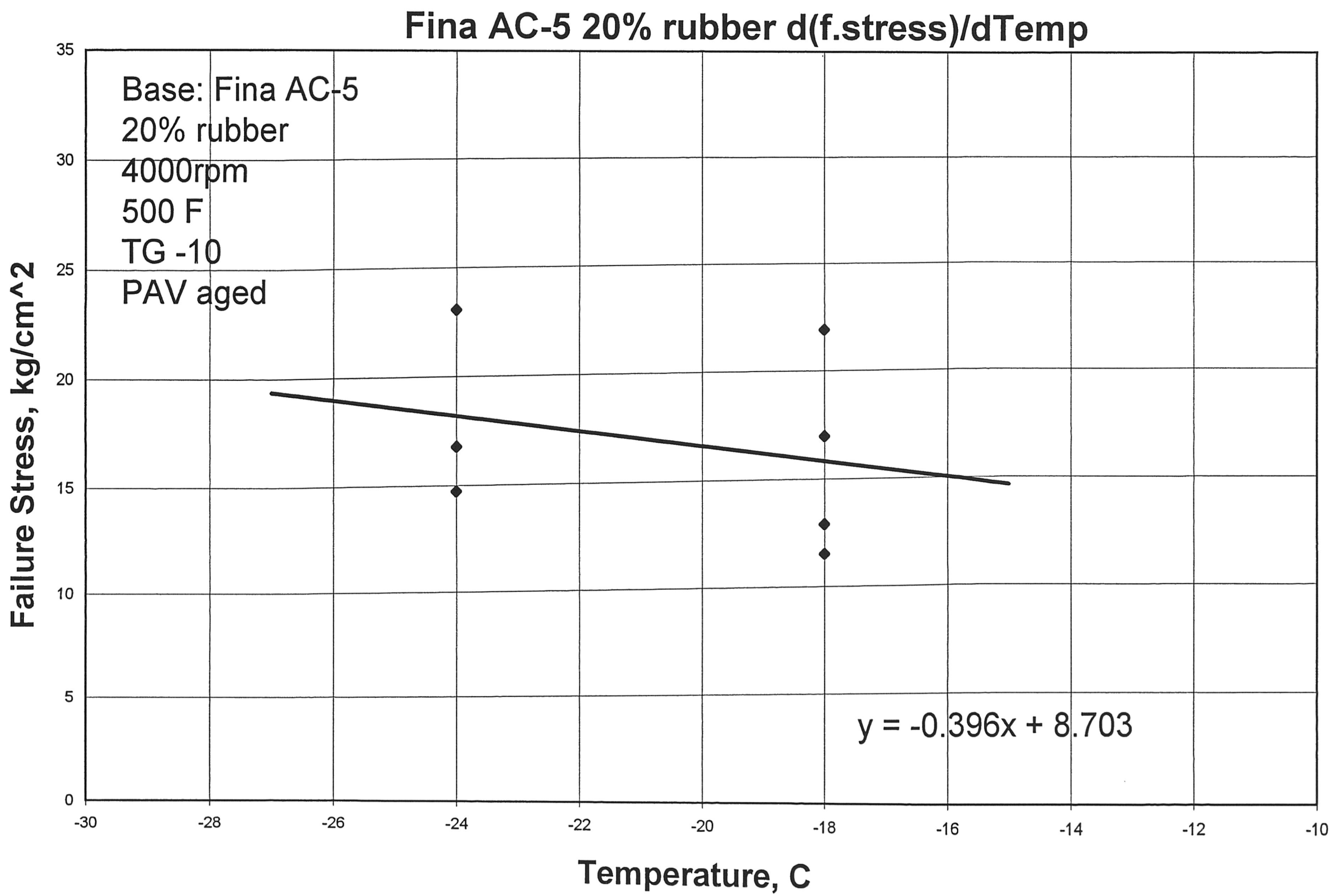

Fina AC-5 TG -40 dstrain/dTemp
Base: Fina AC-5
10% rubber
4000rpm
500 F
TG -40
PAV aged
y = 0.121x + 3.4143
Failure Strain,%
Temperature, C
4
3.5
3
2.5
2
1.5
1
0.5
0
-30
-28
-26
-24
-22
-20
-18
-16
-14
-12
-10

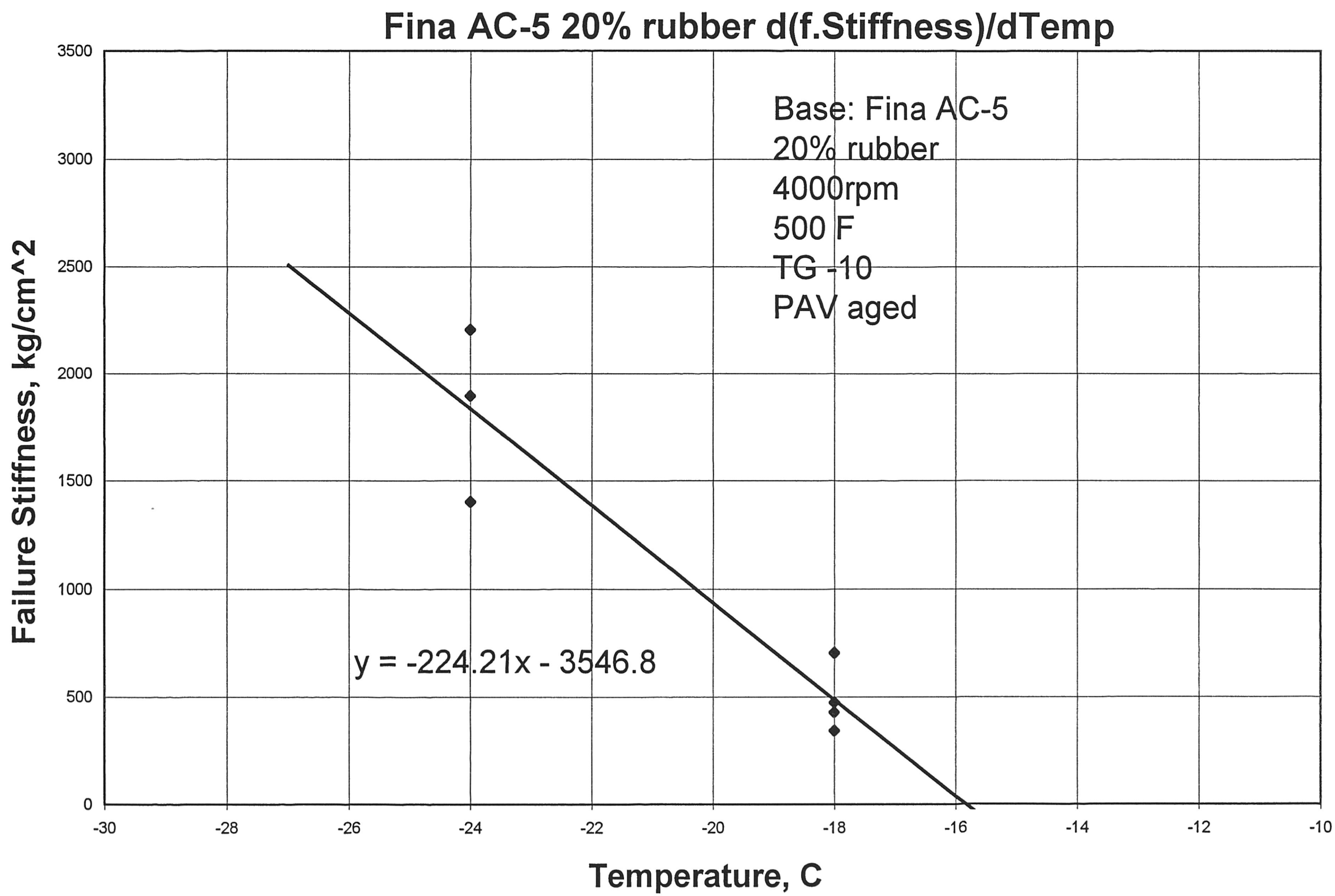

Fina AC-5 TG -40 d(f.stress)/dTemp
Base: Fina AC-5
10% rubber
4000rpm
500 F
TG -40
PAV aged
y = -0.1898x + 10.21
Failure Stress, kg/cm^2
Temperature, C
35
30
25
20
15
10
5
0
-30
-28
-26
-24
-22
-20
-18
-16
-14
-12
-10

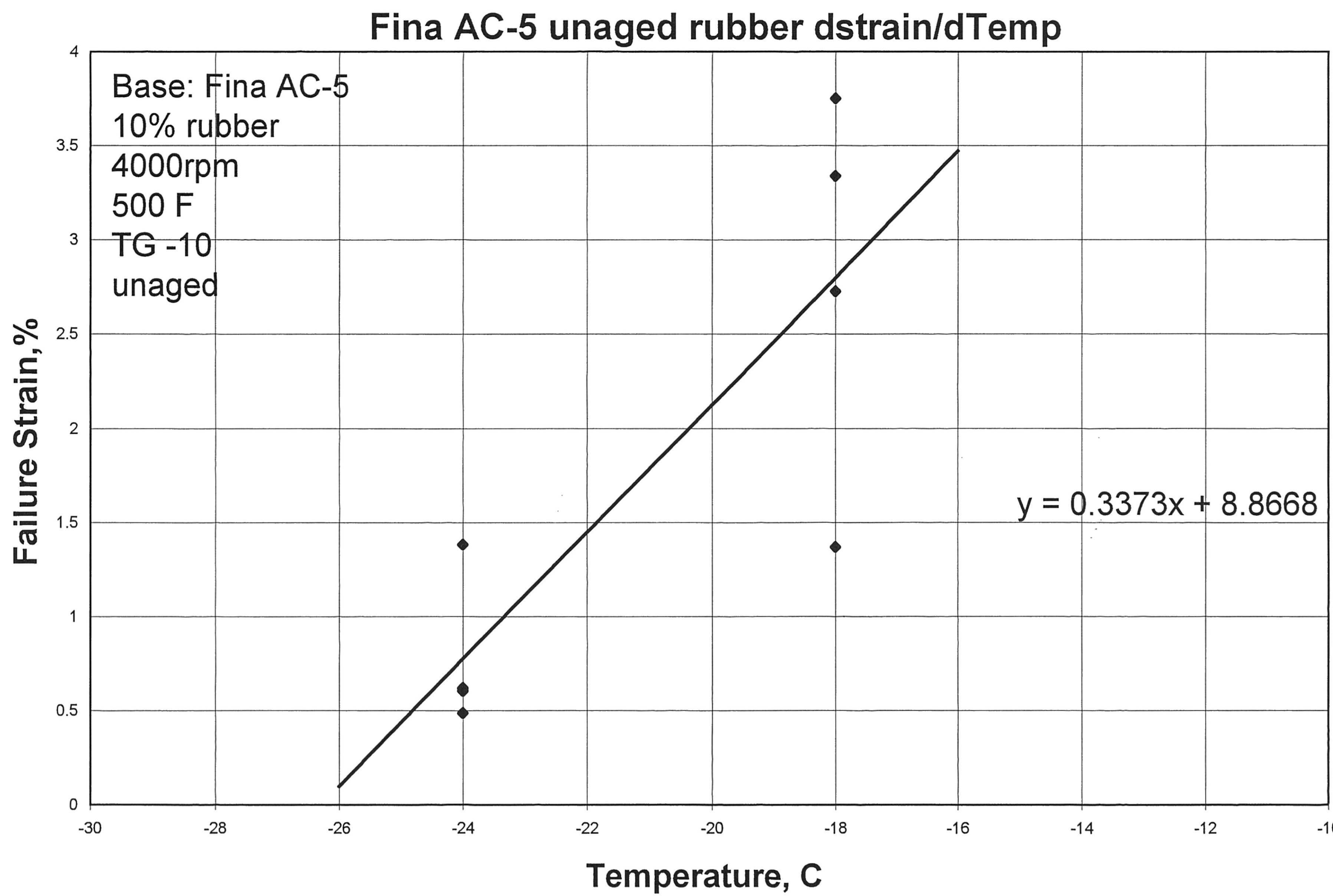
Fina AC-5 TG -40 d(f.stiffness)/dTemp

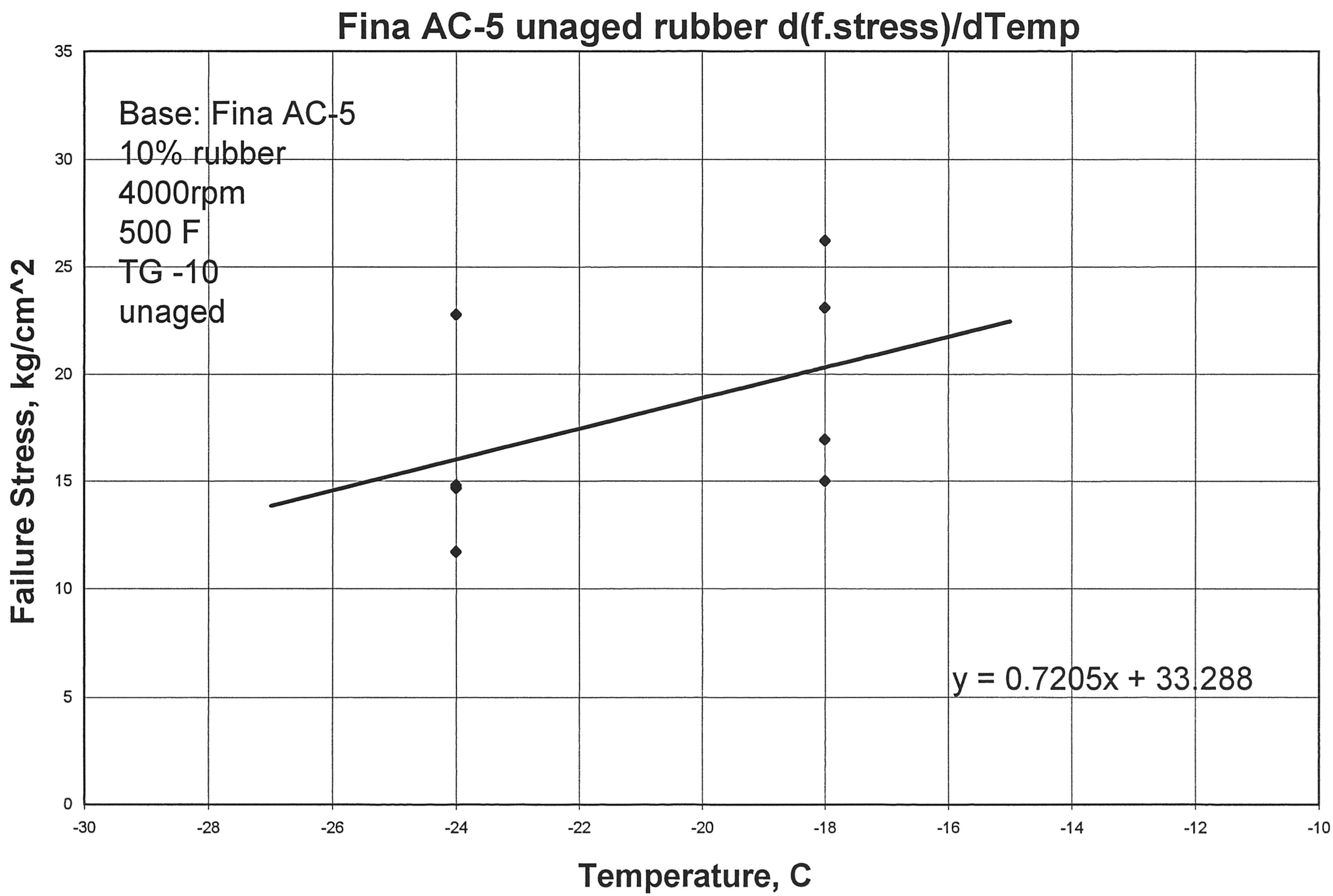


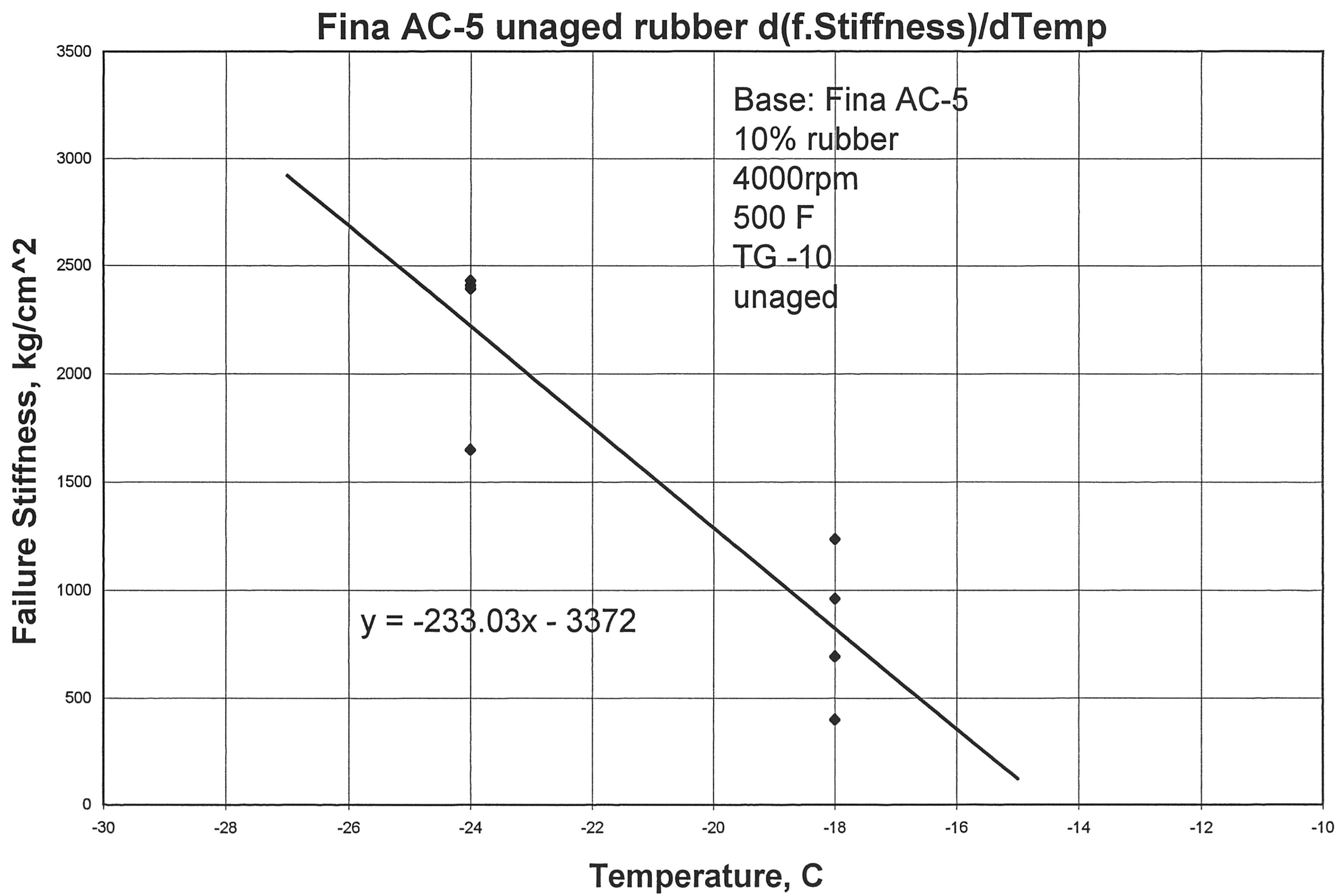

Fina AC-5 20% rubber dstrain/dTemp
Base: Fina AC-5
20% rubber
4000rpm
500 F
TG -10
PAV aged
y = 0.3747x + 10.021
Failure Strain,%
Temperature, C
4
3.5
3
2.5
2
1.5
1
0.5
0
-30
-28
-26
-24
-22
-20
-18
-16
-14
-12
-10


Fina AC-5 20% rubber d(f.stress)/dTemp
Base: Fina AC-5
20% rubber
4000rpm
500 F
TG -10
PAV aged
y = -0.396x + 8.703
Failure Stress, kg/cm^2
Temperature, C
0
5
10
15
20
25
30
35
-30
-28
-26
-24
-22
-20
-18
-16
-14
-12
-10


Fina AC-5 20% rubber d(f.Stiffness)/dTemp
Base: Fina AC-5
20% rubber
4000rpm
500 F
TG -10
PAV aged
y = -224.21x - 3546.8
Failure Stiffness, kg/cm^2
Temperature, C
3500
3000
2500
2000
1500
1000
500
0
-30
-28
-26
-24
-22
-20
-18
-16
-14
-12
-10


Fina AC-5 unaged rubber dstrain/dTemp
Base: Fina AC-5
10% rubber
4000rpm
500 F
TG -10
unaged
y = 0.3373x + 8.8668
Failure Strain,%
Temperature, C
0
0.5
1
1.5
2
2.5
3
3.5
4
-30
-28
-26
-24
-22
-20
-18
-16
-14
-12
-10

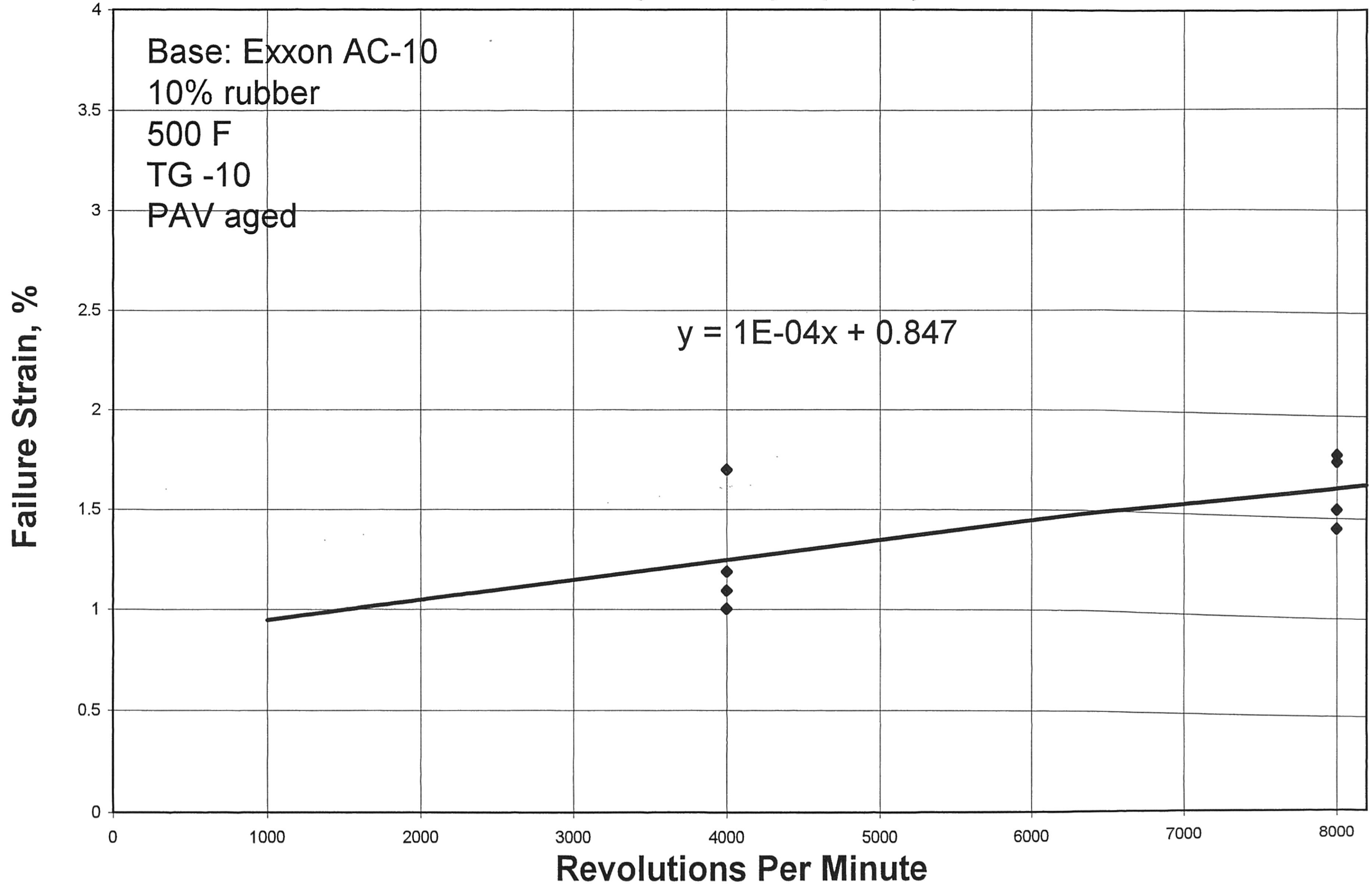

Fina AC-5 unaged rubber d(f.stress)/dTemp
Base: Fina AC-5
10% rubber
4000rpm
500 F
TG -10
unaged
y = 0.7205x + 33.288
Failure Stress, kg/cm^2
Temperature, C
35
30
25
20
15
10
5
0
-30
-28
-26
-24
-22
-20
-18
-16
-14
-12
-10

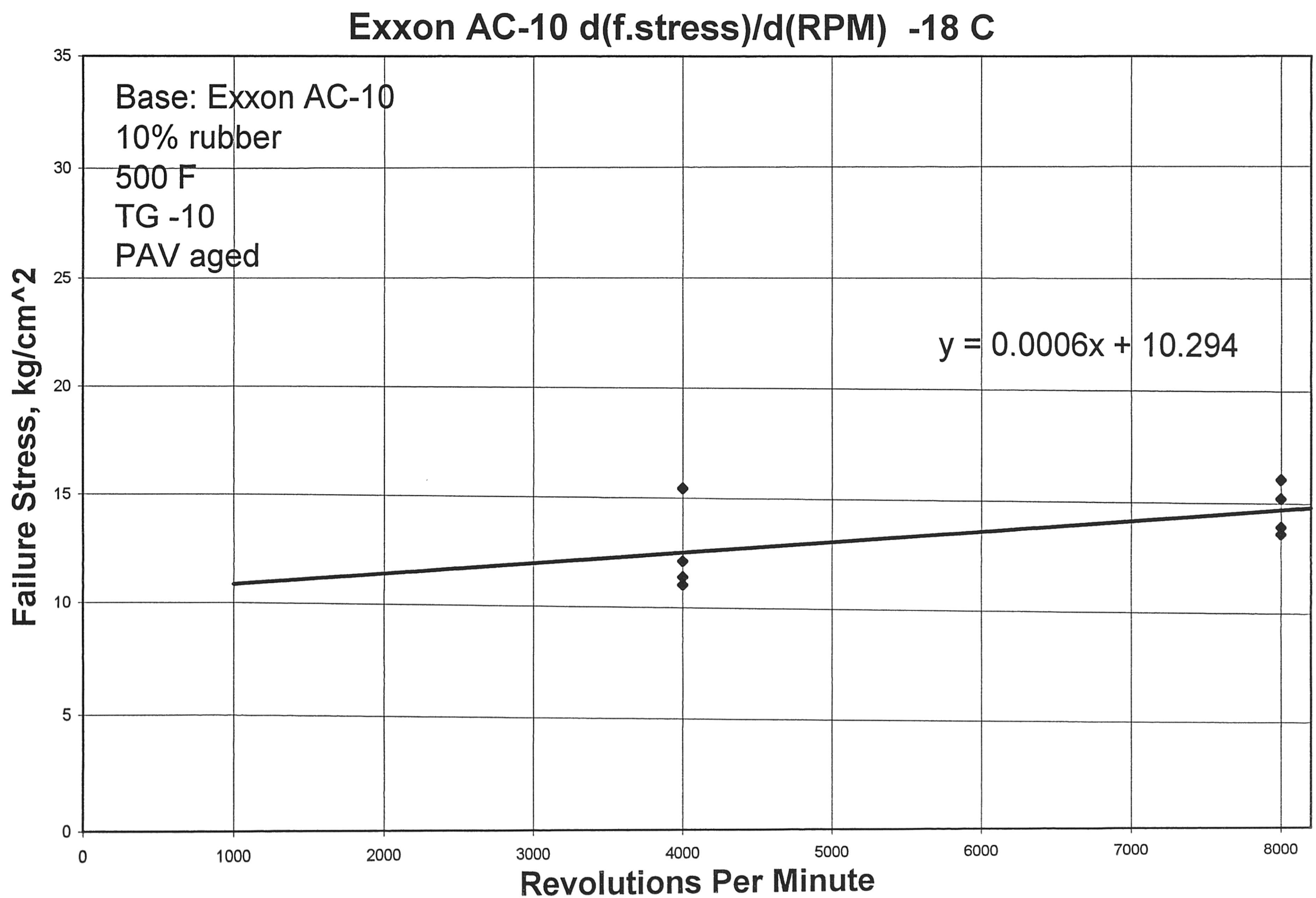


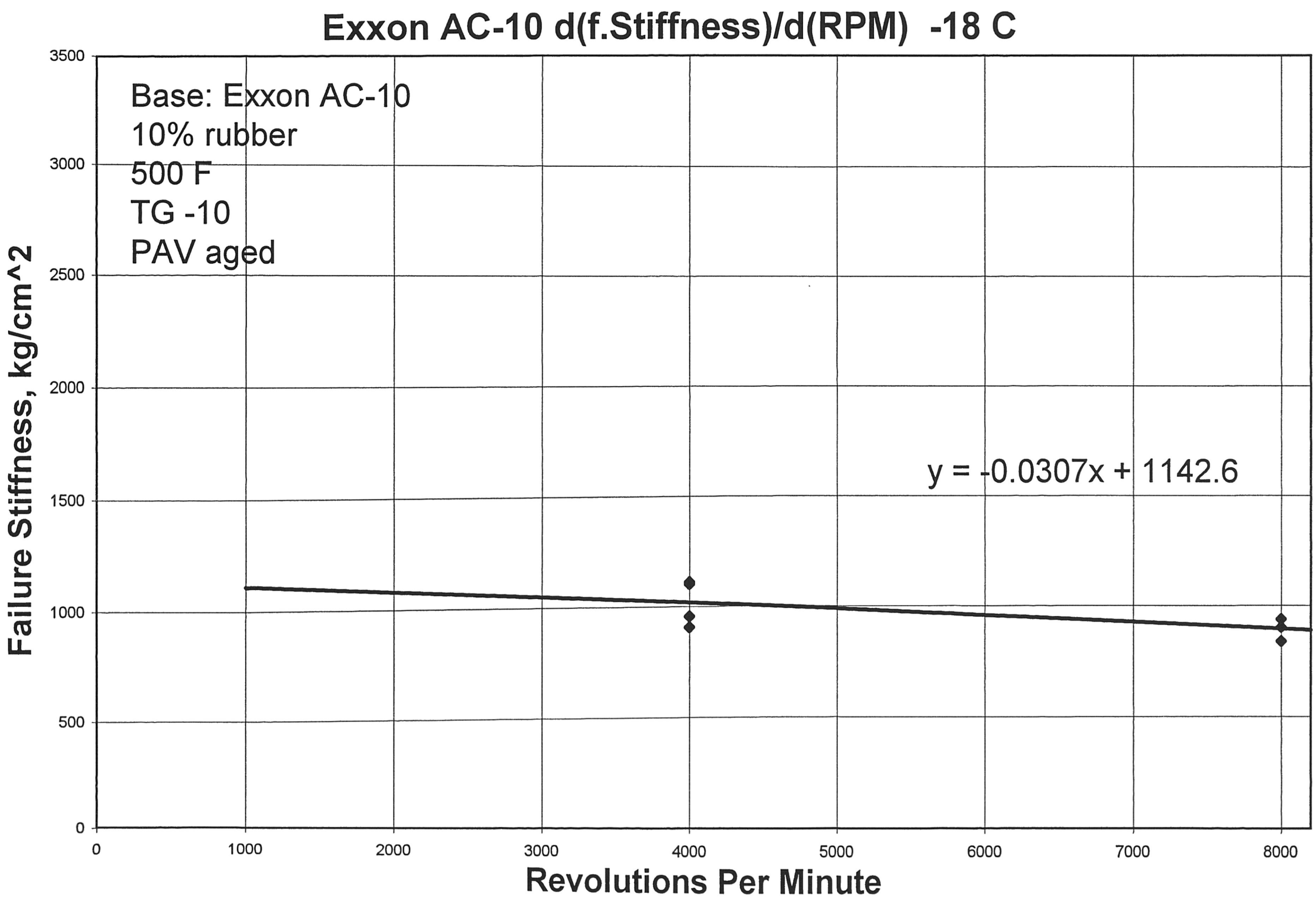
Fina AC-5 unaged rubber d(f.Stiffness)/dTemp
Base: Fina AC-5
10% rubber
4000rpm
500 F
TG -10
unaged
y = -233.03x - 3372
Failure Stiffness, kg/cm^2
3500
3000
2500
2000
1500
1000
500
0
-30
-28
-26
-24
-22
-20
-18
-16
-14
-12
-10
Temperature, C

Appendix I: Curing Condition Dependence of Failure Properties

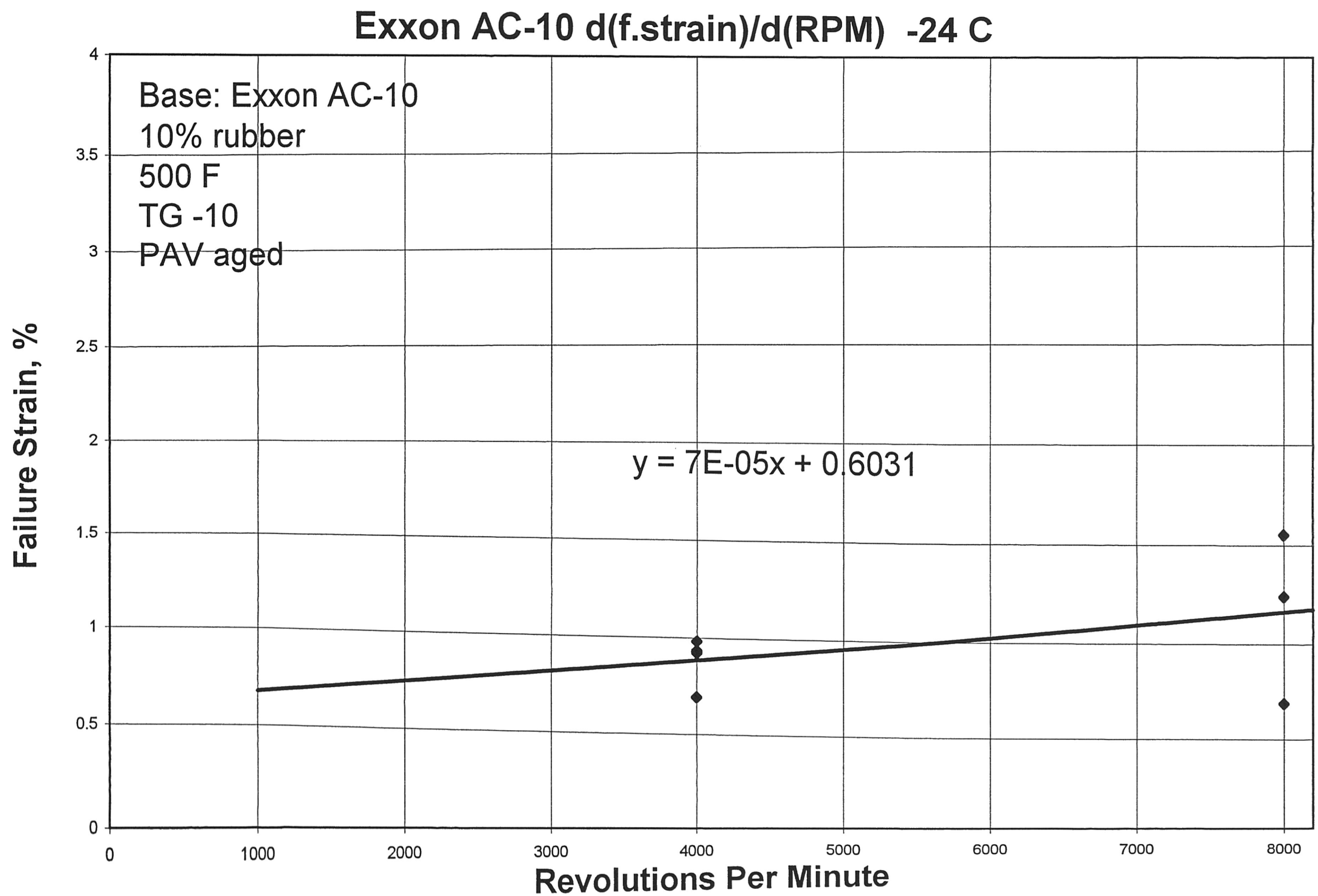
Exxon AC-10 d(f.strain)/d(RPM) -18 C

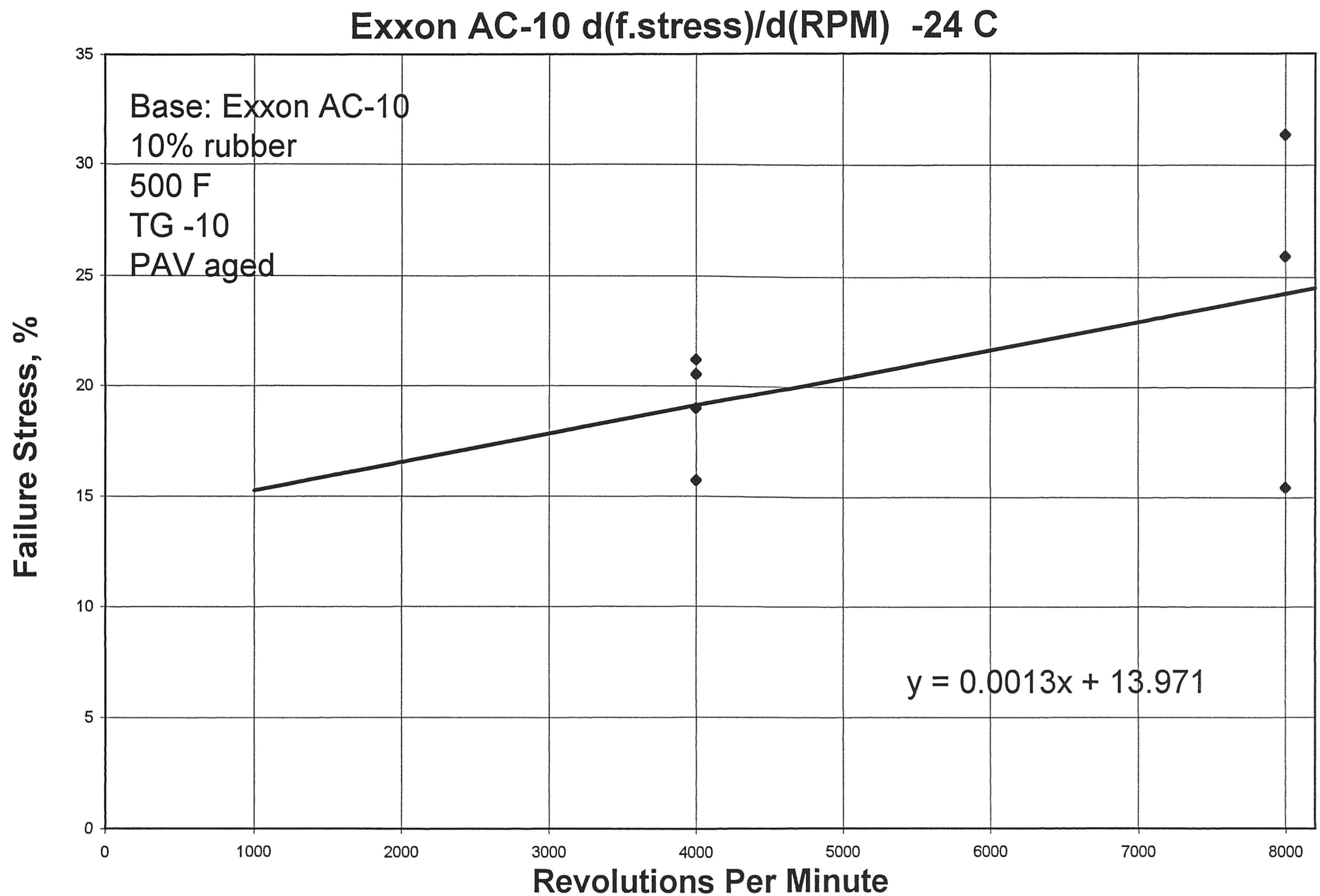


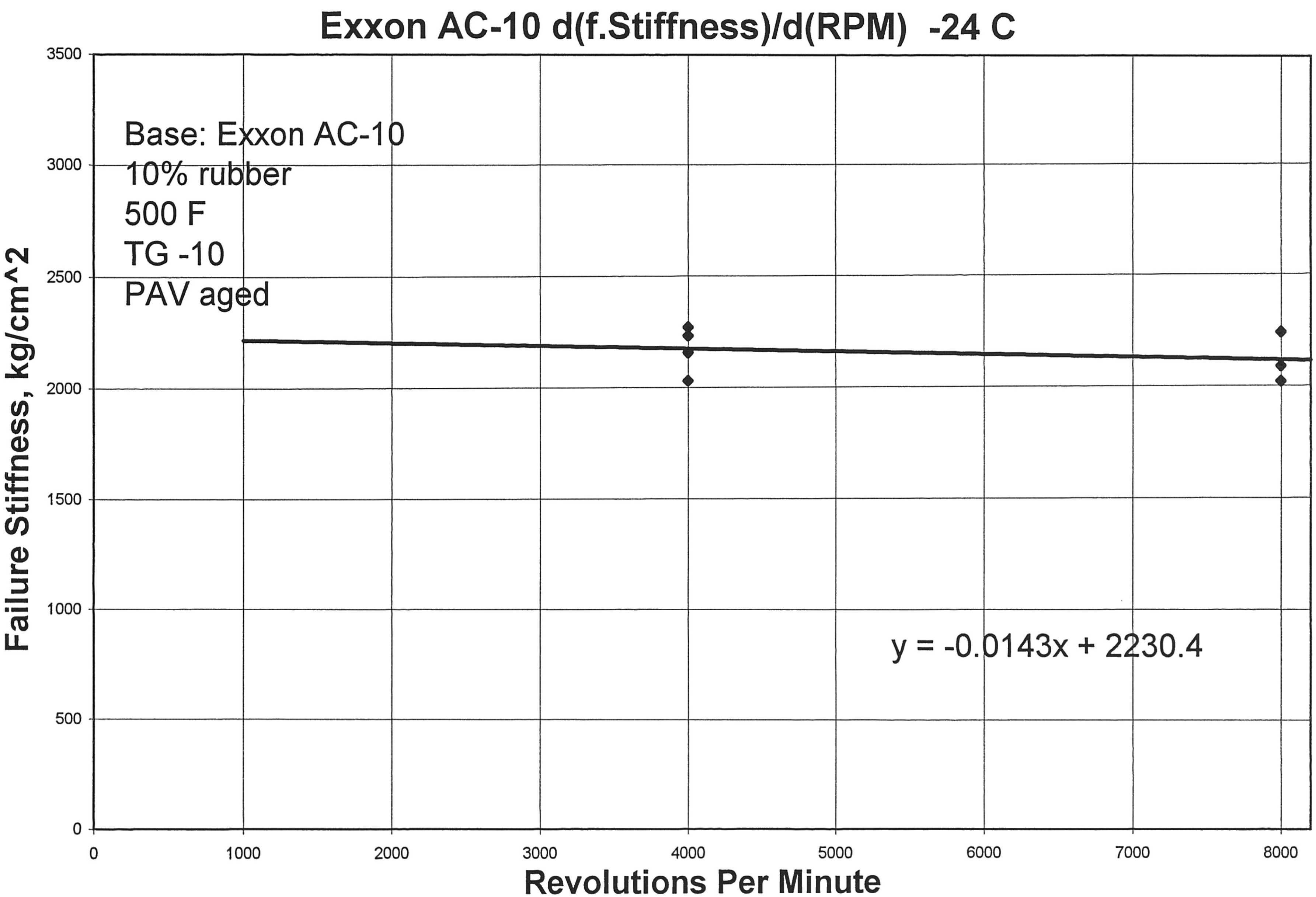

Exxon AC-10 d(f.stress)/d(RPM) -18 C
Base: Exxon AC-10
10% rubber
500 F
TG -10
PAV aged
y = 0.0006x + 10.294
Failure Stress, kg/cm^2
Revolutions Per Minute
0
5
10
15
20
25
30
35
0
1000
2000
3000
4000
5000
6000
7000
8000

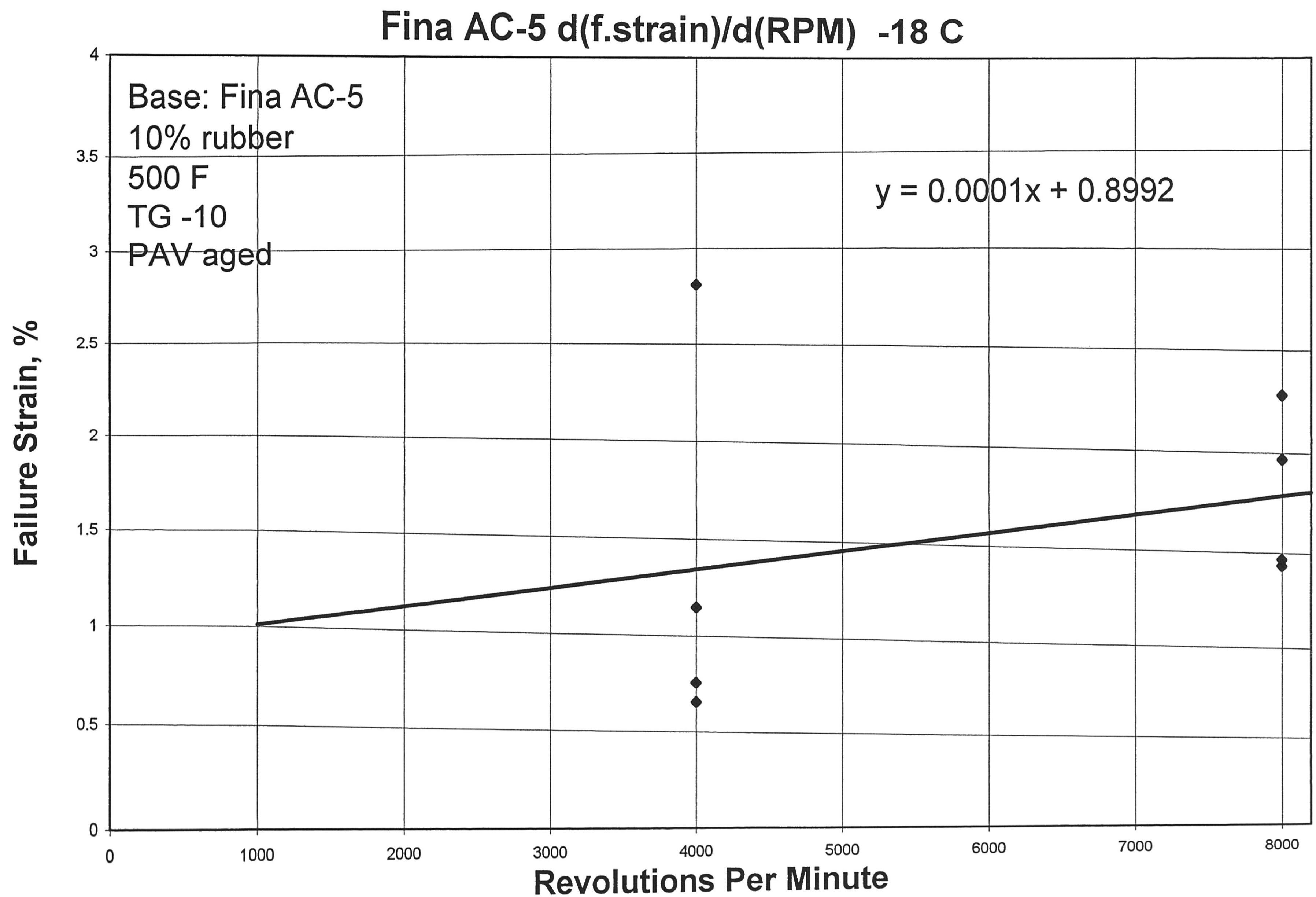


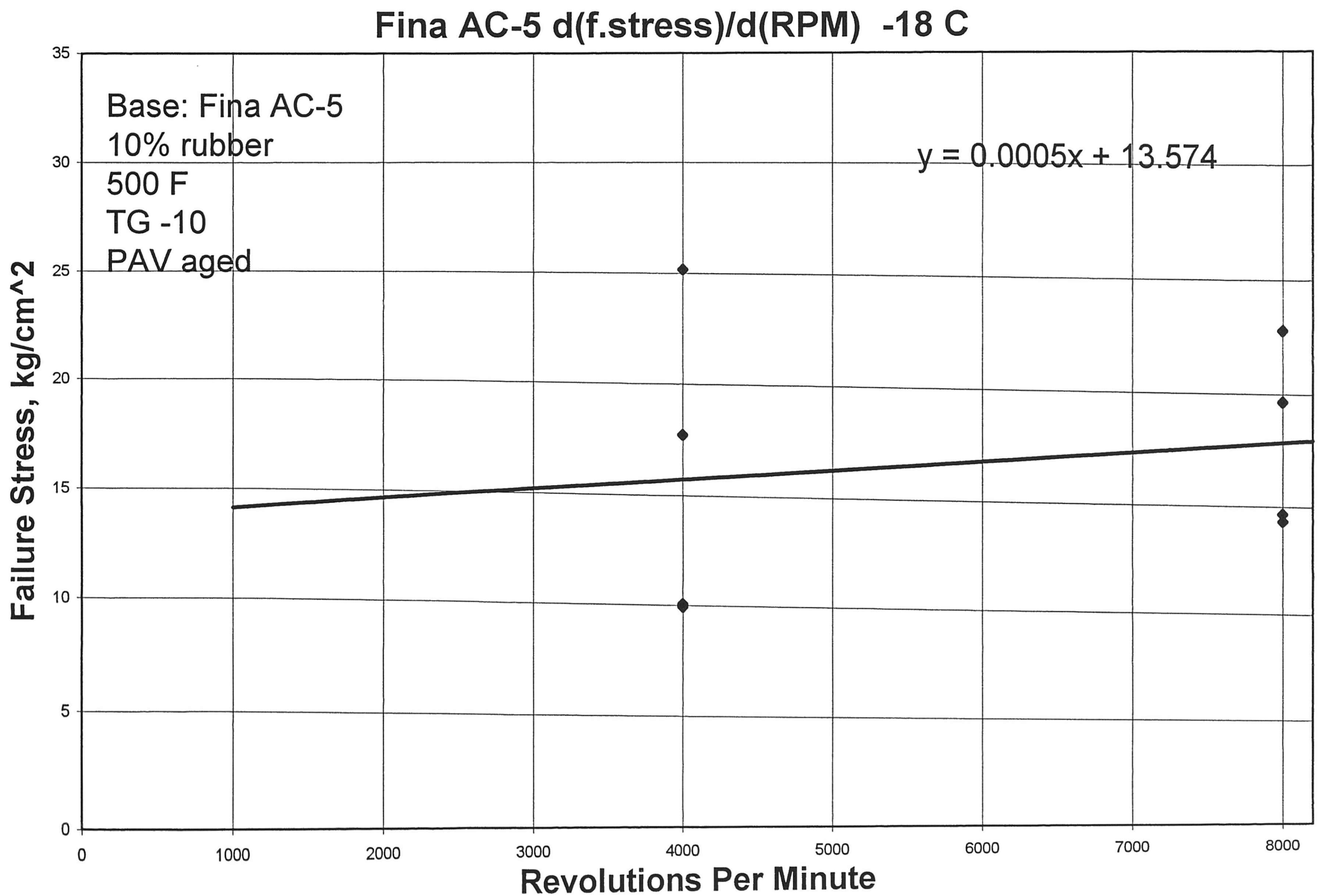
Exxon AC-10 d(f.Stiffness)/d(RPM) -18 C
Base: Exxon AC-10
10% rubber
500 F
TG -10
PAV aged
y = -0.0307x + 1142.6
Failure Stiffness, kg/cm^2
Revolutions Per Minute
3500
3000
2500
2000
1500
1000
500
0
0
1000
2000
3000
4000
5000
6000
7000
8000

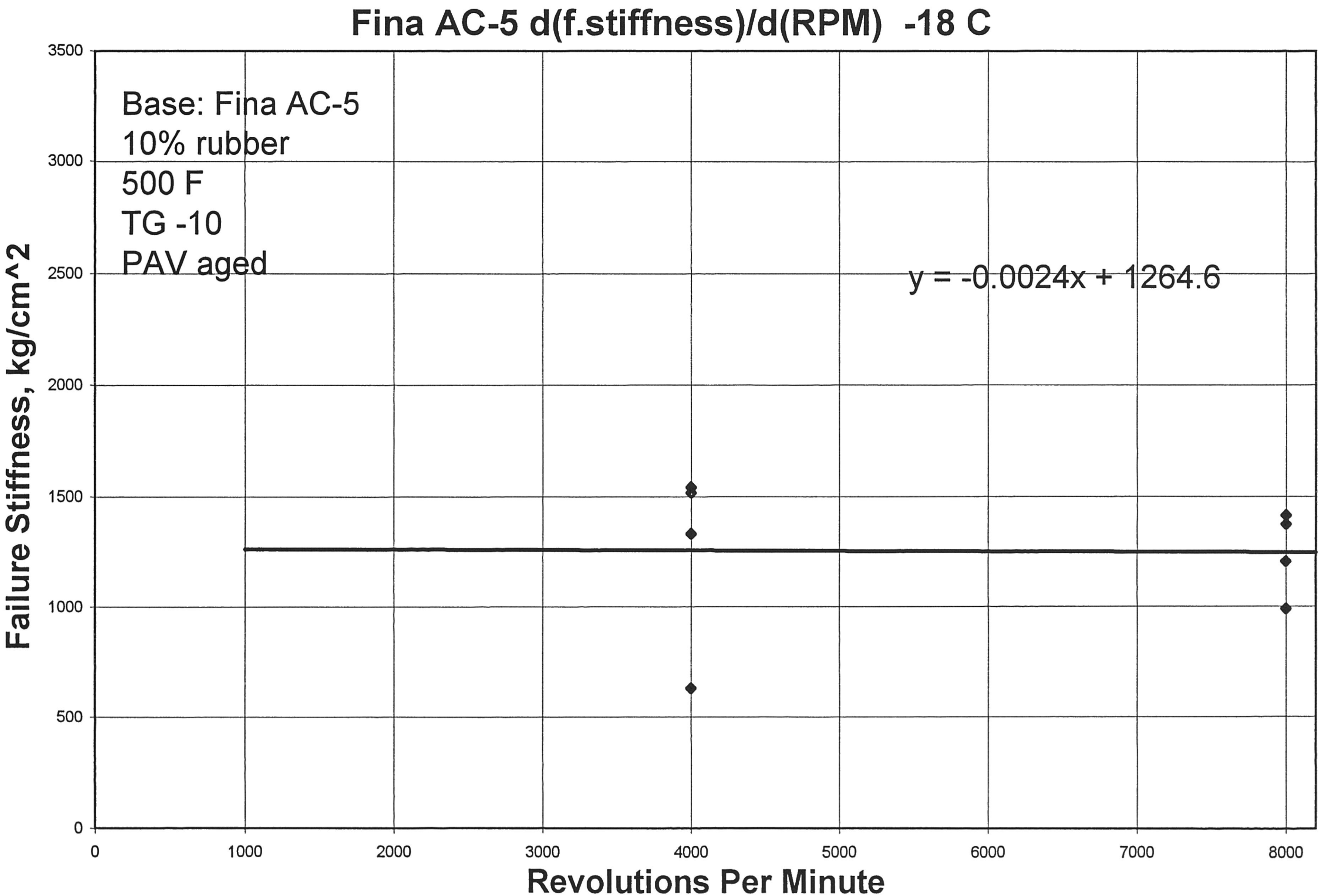

Exxon AC-10 d(f.strain)/d(RPM) -24 C
Base: Exxon AC-10
10% rubber
500 F
TG -10
PAV aged
y = 7E-05x + 0.6031
Failure Strain, %
Revolutions Per Minute
0
0.5
1
1.5
2
2.5
3
3.5
4
1000
2000
3000
4000
5000
6000
7000
8000

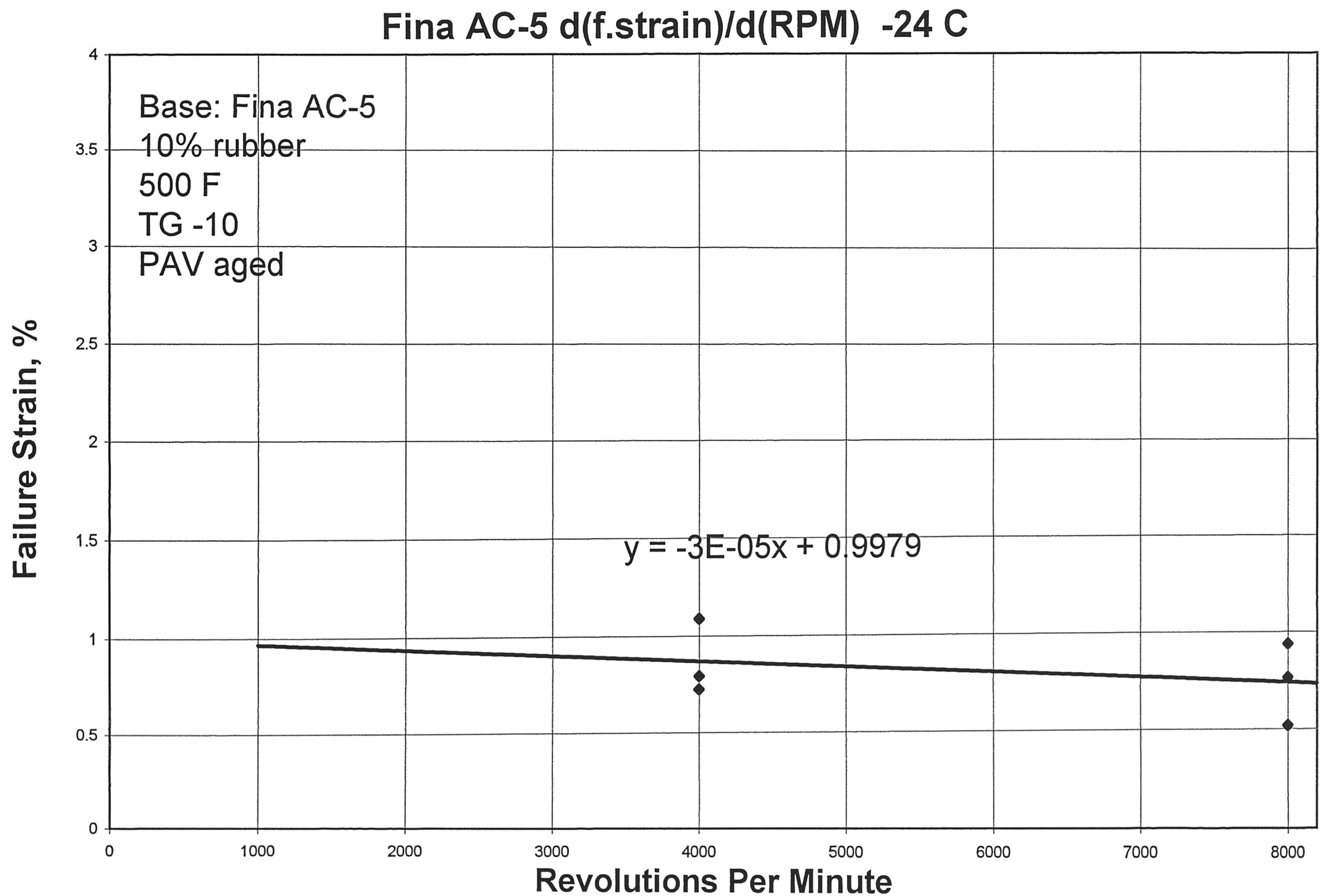

Exxon AC-10 d(f.stress)/d(RPM) -24 C
Base: Exxon AC-10
10% rubber
500 F
TG -10
PAV aged
y = 0.0013x + 13.971
Failure Stress, %
Revolutions Per Minute
0
5
10
15
20
25
30
35
1000
2000
3000
4000
5000
6000
7000
8000


Exxon AC-10 d(f.Stiffness)/d(RPM) -24 C
Base: Exxon AC-10
10% rubber
500 F
TG -10
PAV aged
y = -0.0143x + 2230.4
Failure Stiffness, kg/cm^2
Revolutions Per Minute
0
500
1000
1500
2000
2500
3000
3500
0
1000
2000
3000
4000
5000
6000
7000
8000

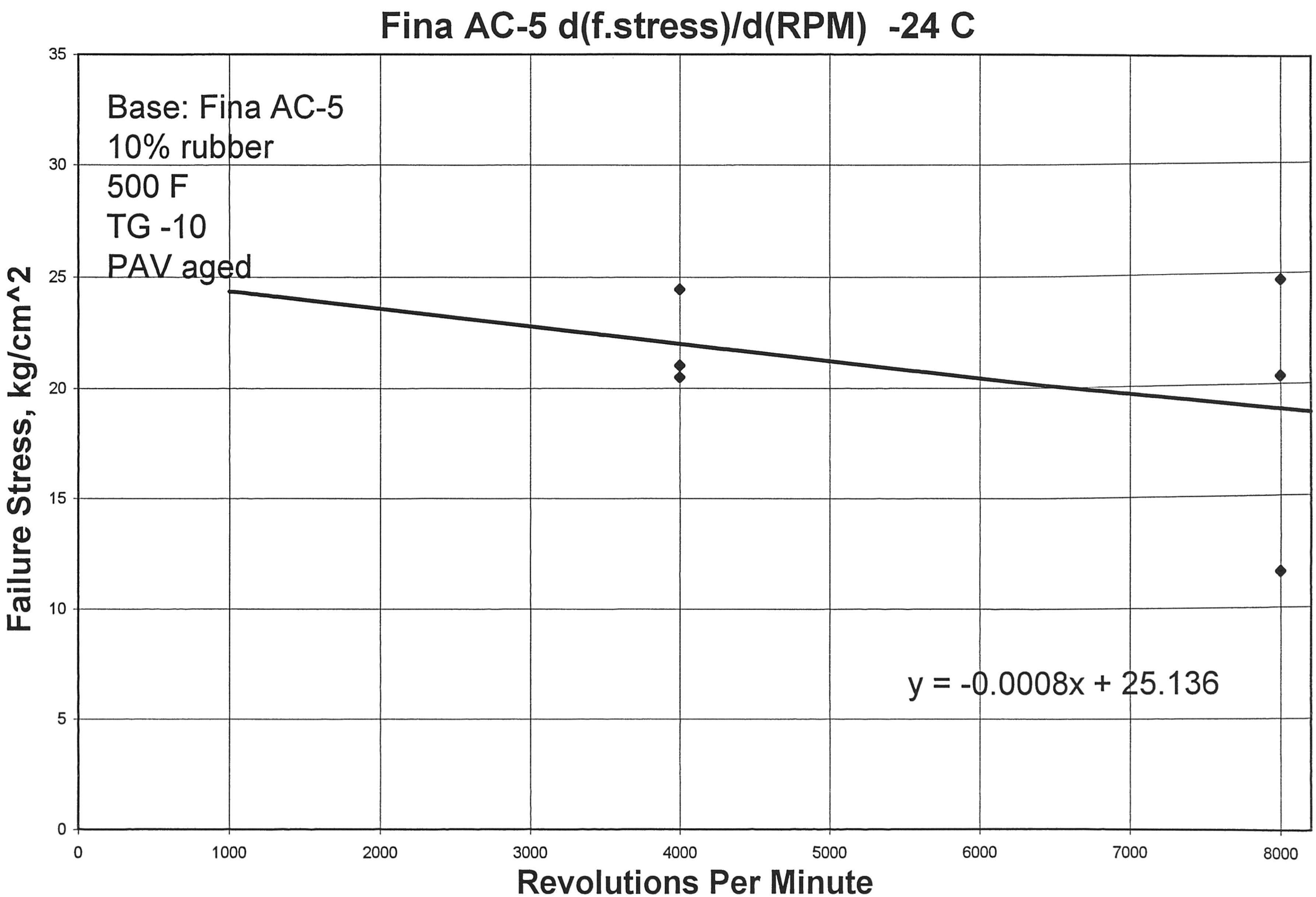

Fina AC-5 d(f.strain)/d(RPM) -18 C
Base: Fina AC-5
10% rubber
500 F
TG -10
PAV aged
y = 0.0001x + 0.8992
Failure Strain, %
Revolutions Per Minute
0
0.5
1
1.5
2
2.5
3
3.5
4
0
1000
2000
3000
4000
5000
6000
7000
8000


Fina AC-5 d(f.stress)/d(RPM) -18 C
Base: Fina AC-5
10% rubber
500 F
TG -10
PAV aged
y = 0.0005x + 13.574
Failure Stress, kg/cm^2
Revolutions Per Minute
0
5
10
15
20
25
30
35
0
1000
2000
3000
4000
5000
6000
7000
8000

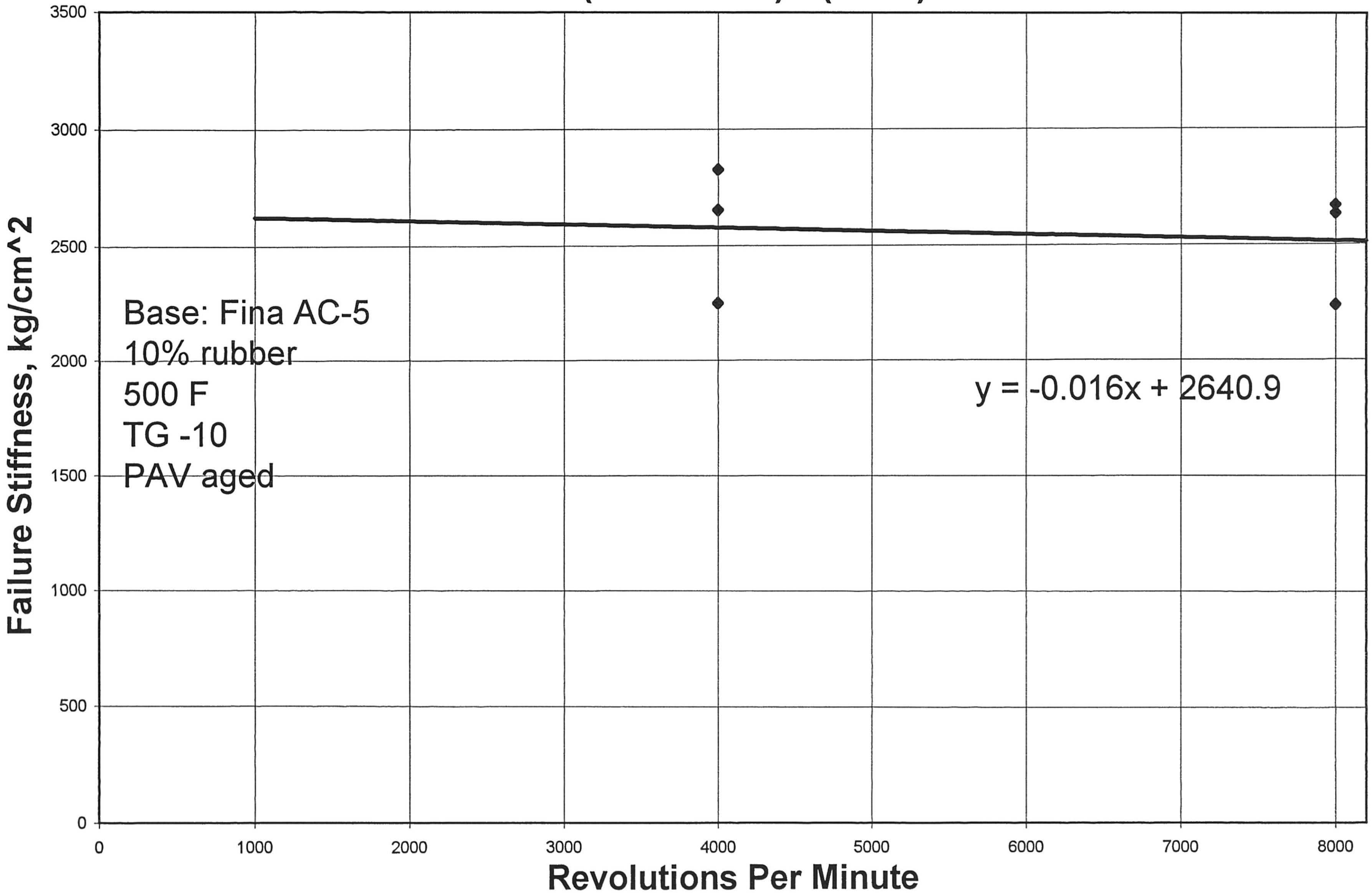

Fina AC-5 d(f.stiffness)/d(RPM) -18 C
Base: Fina AC-5
10% rubber
500 F
TG -10
PAV aged
y = -0.0024x + 1264.6
Failure Stiffness, kg/cm^2
Revolutions Per Minute
0
500
1000
1500
2000
2500
3000
3500
0
1000
2000
3000
4000
5000
6000
7000
8000



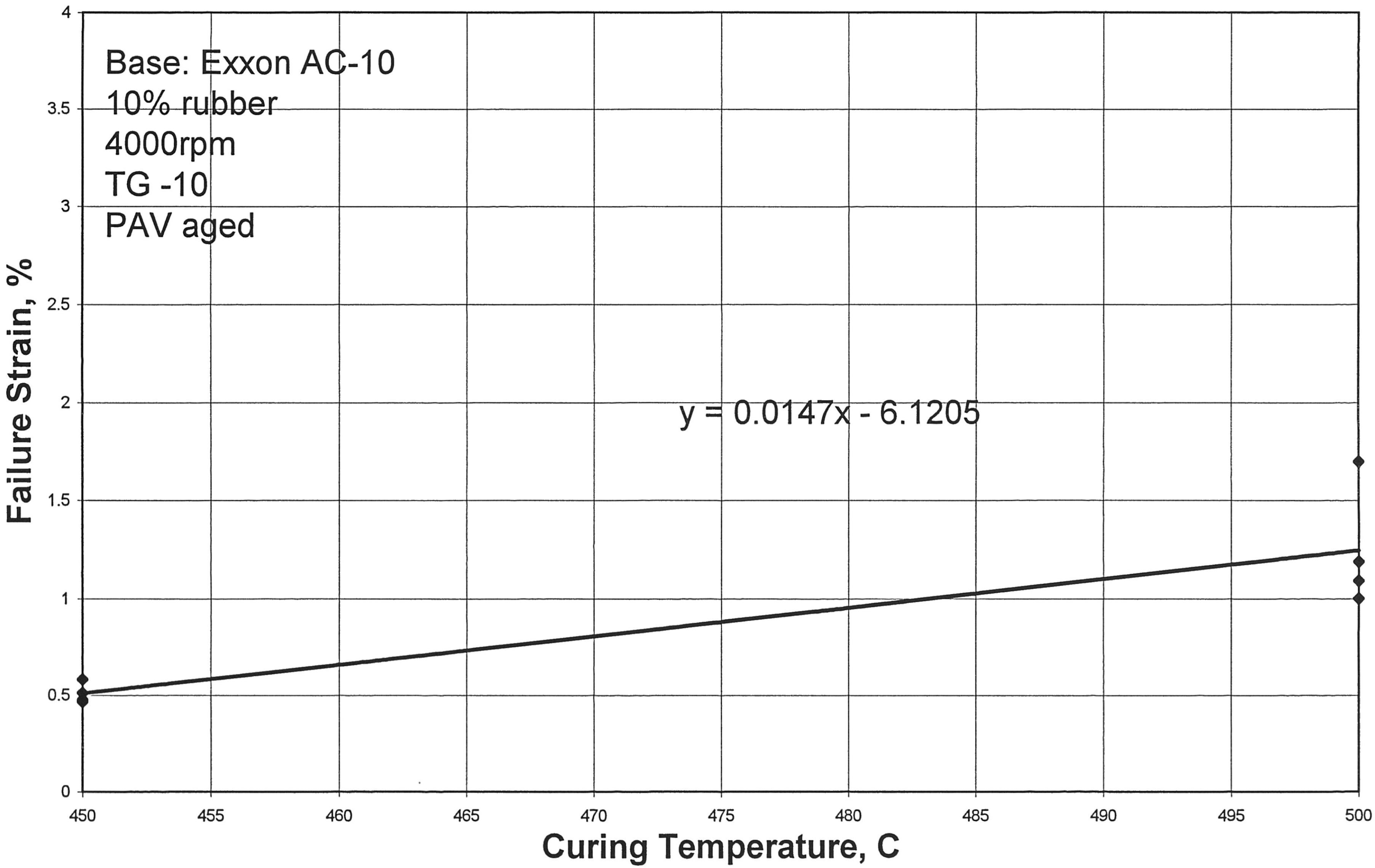
Fina AC-5 d(f.strain)/d(RPM) -24 C
Base: Fina AC-5
10% rubber
500 F
TG -10
PAV aged
y = -3E-05x + 0.9979
Failure Strain, %
Revolutions Per Minute
0
0.5
1
1.5
2
2.5
3
3.5
4
0
1000
2000
3000
4000
5000
6000
7000
8000


Fina AC-5 d(f.stress)/d(RPM) -24 C
Base: Fina AC-5
10% rubber
500 F
TG -10
PAV aged
y = -0.0008x + 25.136
Failure Stress, kg/cm^2
Revolutions Per Minute
0
5
10
15
20
25
30
35
0
1000
2000
3000
4000
5000
6000
7000
8000

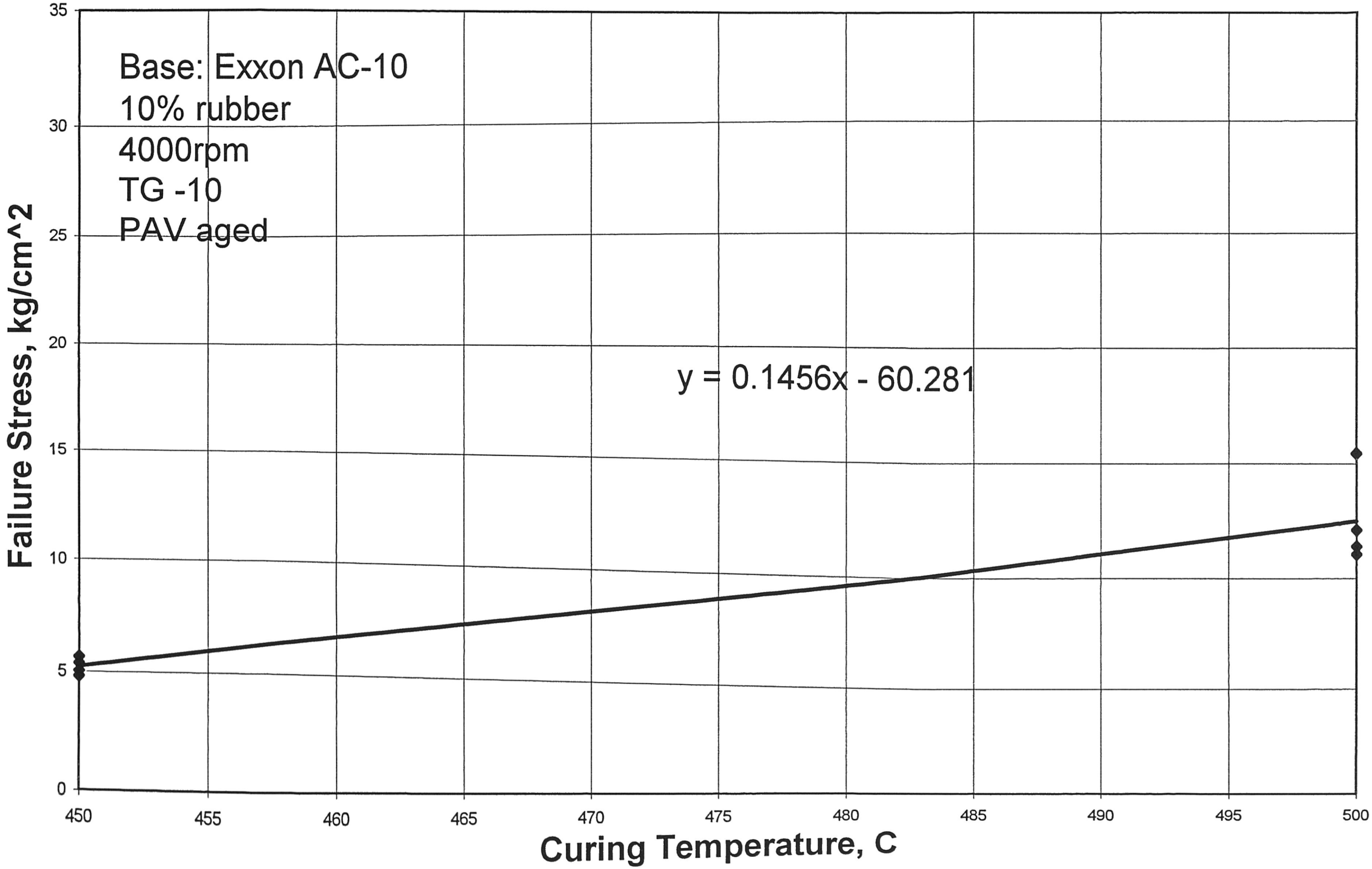
Fina AC-5 d(f.Stiffness)/d(RPM) -24 C

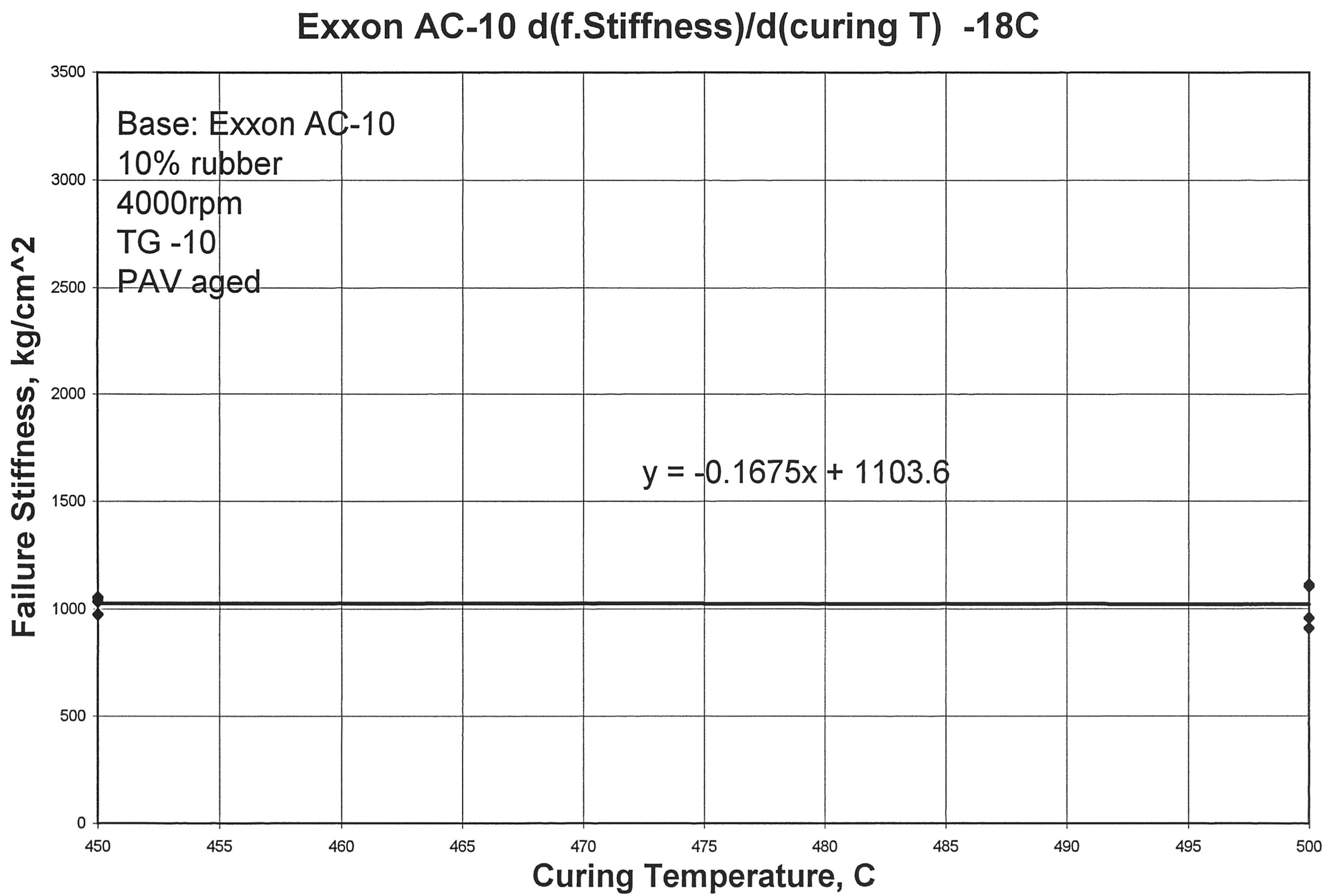


Exxon AC-10 d(f.strain)/d(curing T) -18C

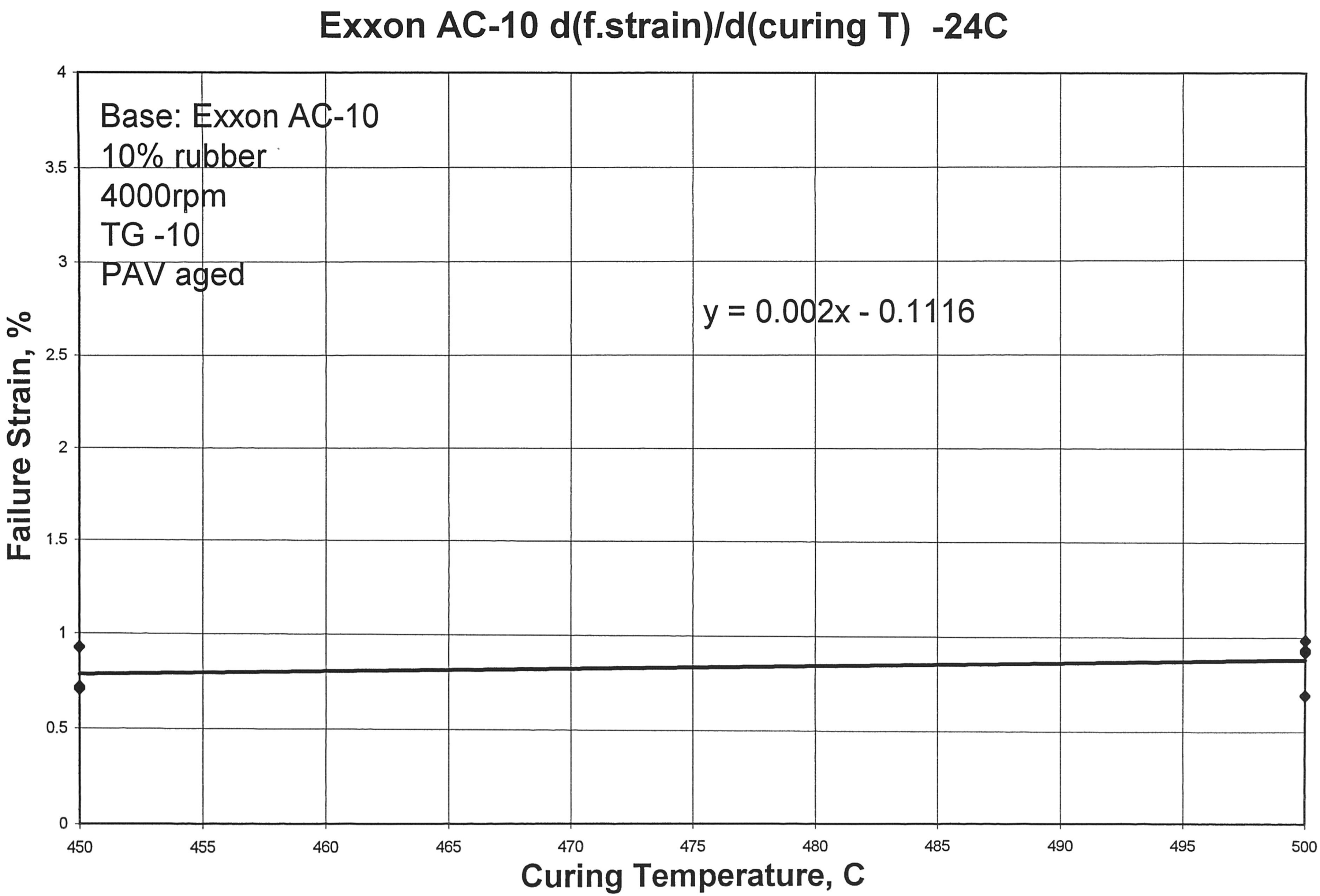


Exxon AC-10 d(f.stress)/d(curing T) -18C

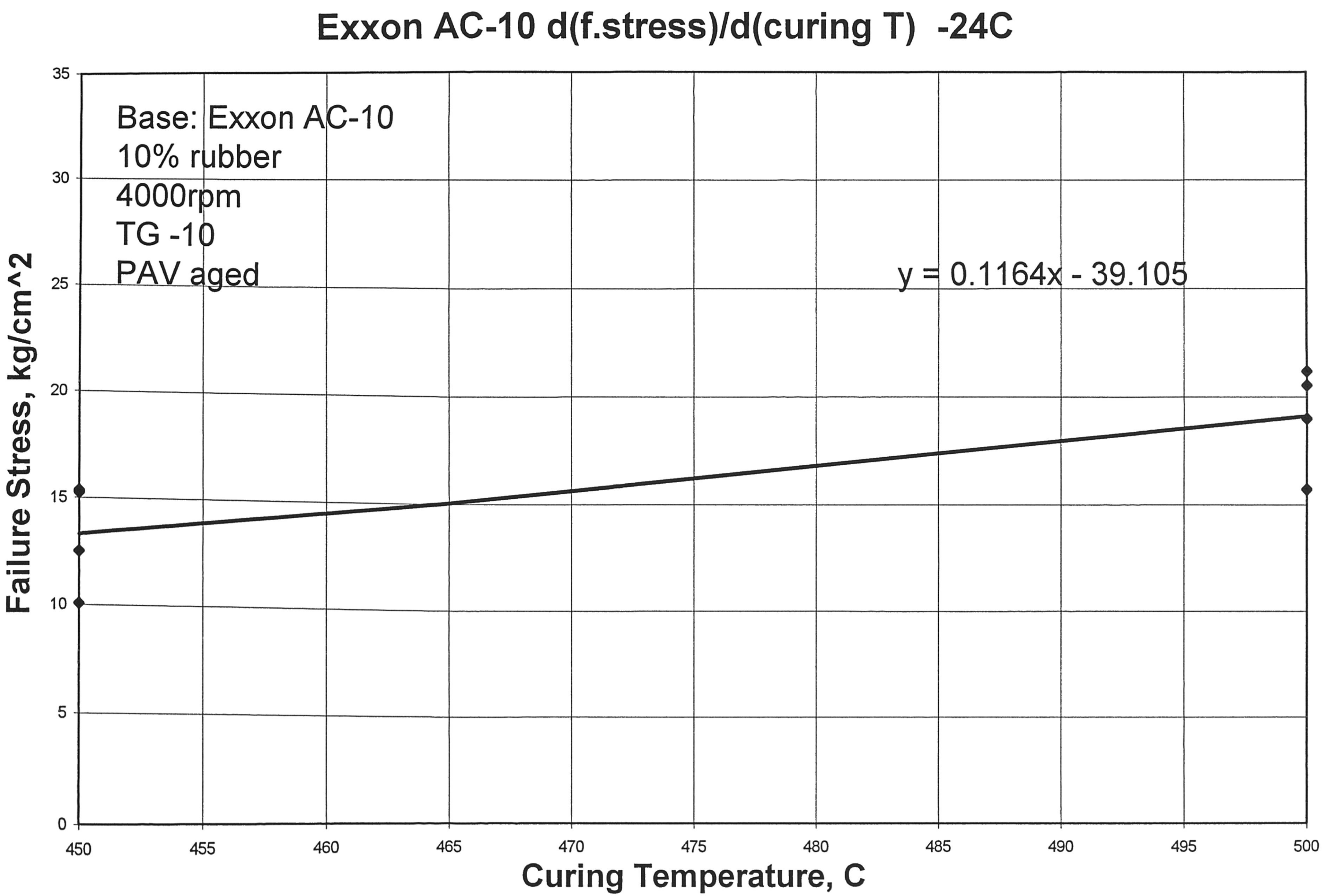


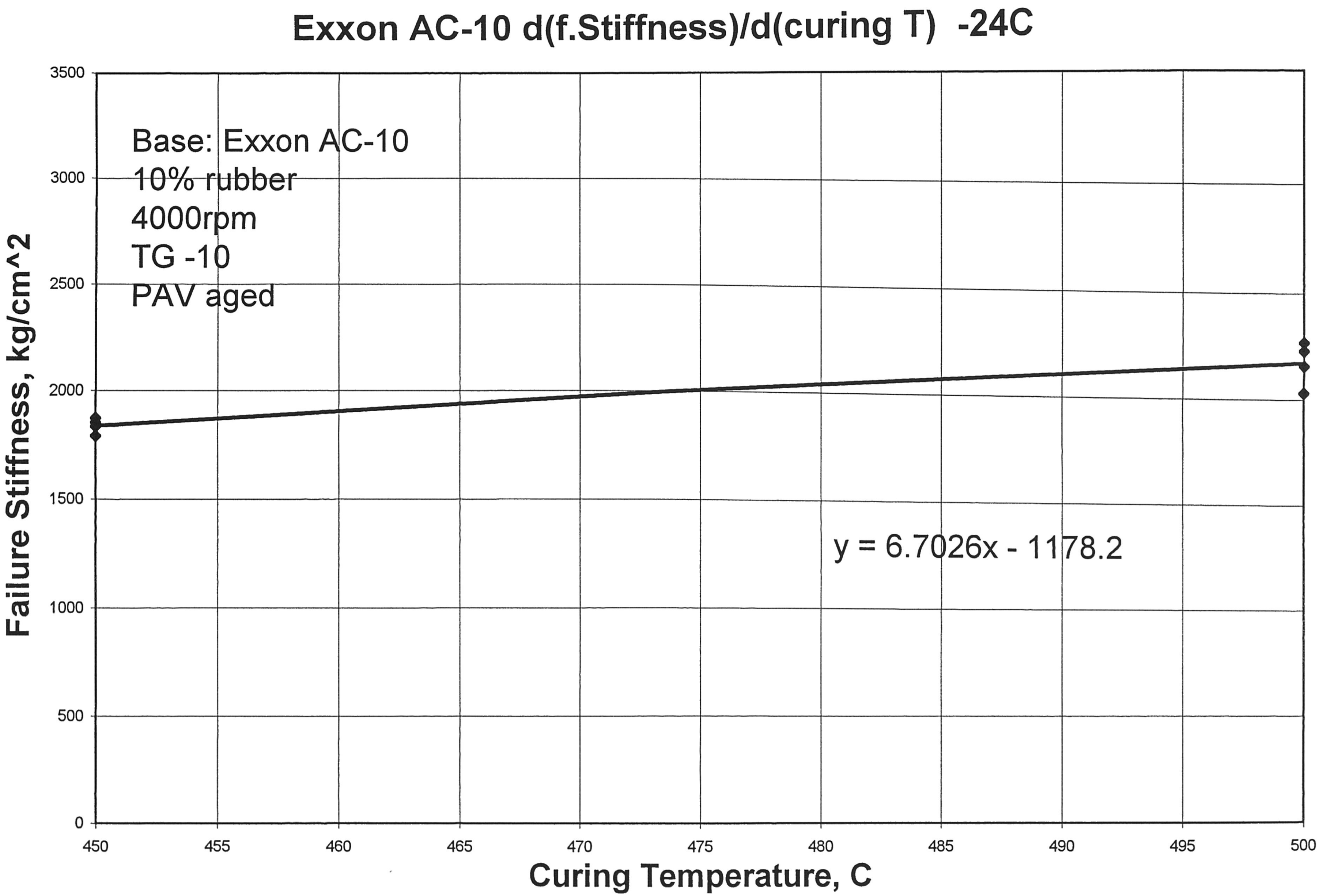


Exxon AC-10 d(f.Stiffness)/d(curing T) -18C
Base: Exxon AC-10
10% rubber
4000rpm
TG -10
PAV aged
y = -0.1675x + 1103.6
Failure Stiffness, kg/cm^2
3500
3000
2500
2000
1500
1000
500
0
450
455
460
465
470
475
480
485
490
495
500
Curing Temperature, C

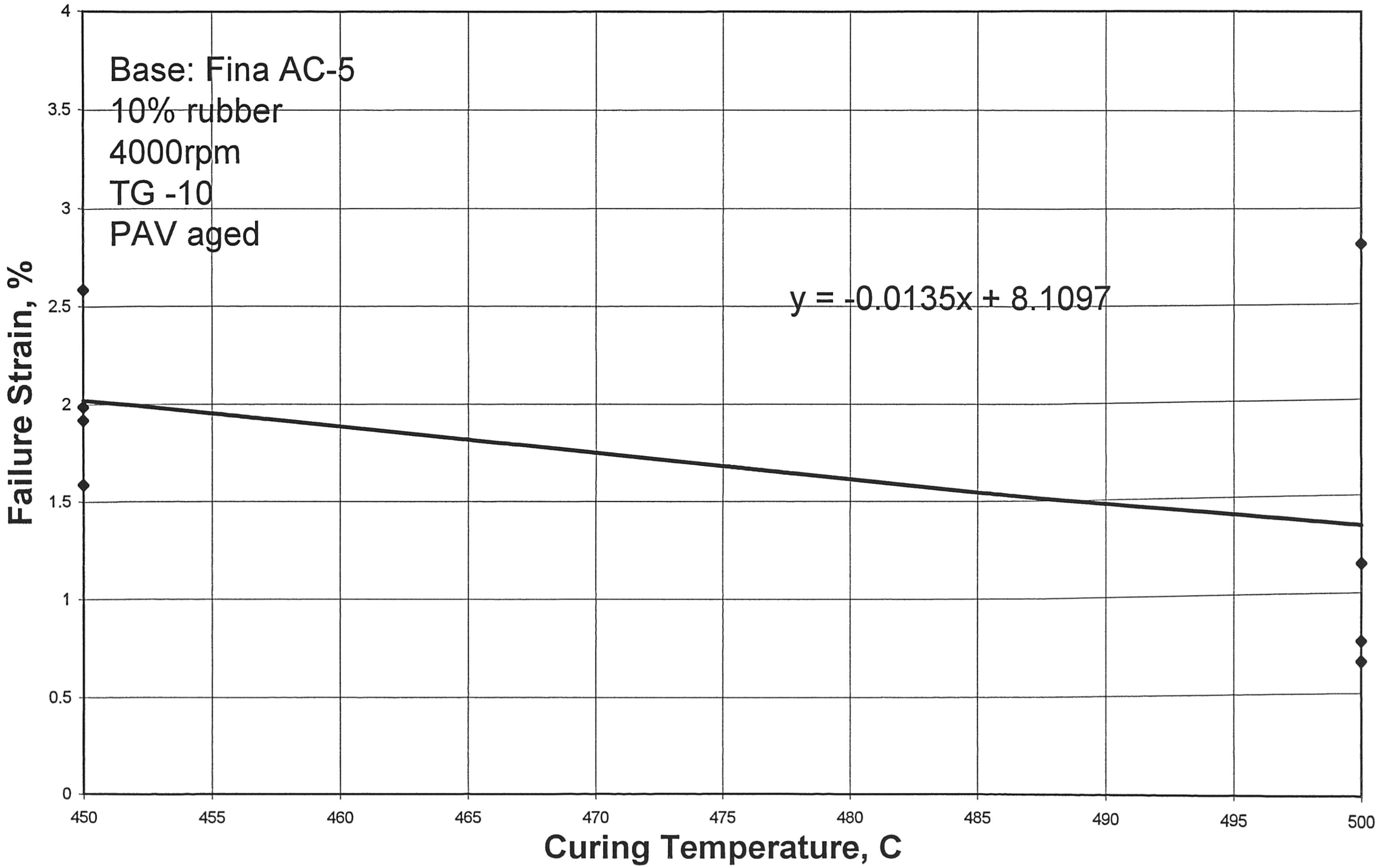


Exxon AC-10 d(f.strain)/d(curing T) -24C
Base: Exxon AC-10
10% rubber
4000rpm
TG -10
PAV aged
y = 0.002x - 0.1116
Failure Strain, %
4
3.5
3
2.5
2
1.5
1
0.5
0
450
455
460
465
470
475
480
485
490
495
500
Curing Temperature, C

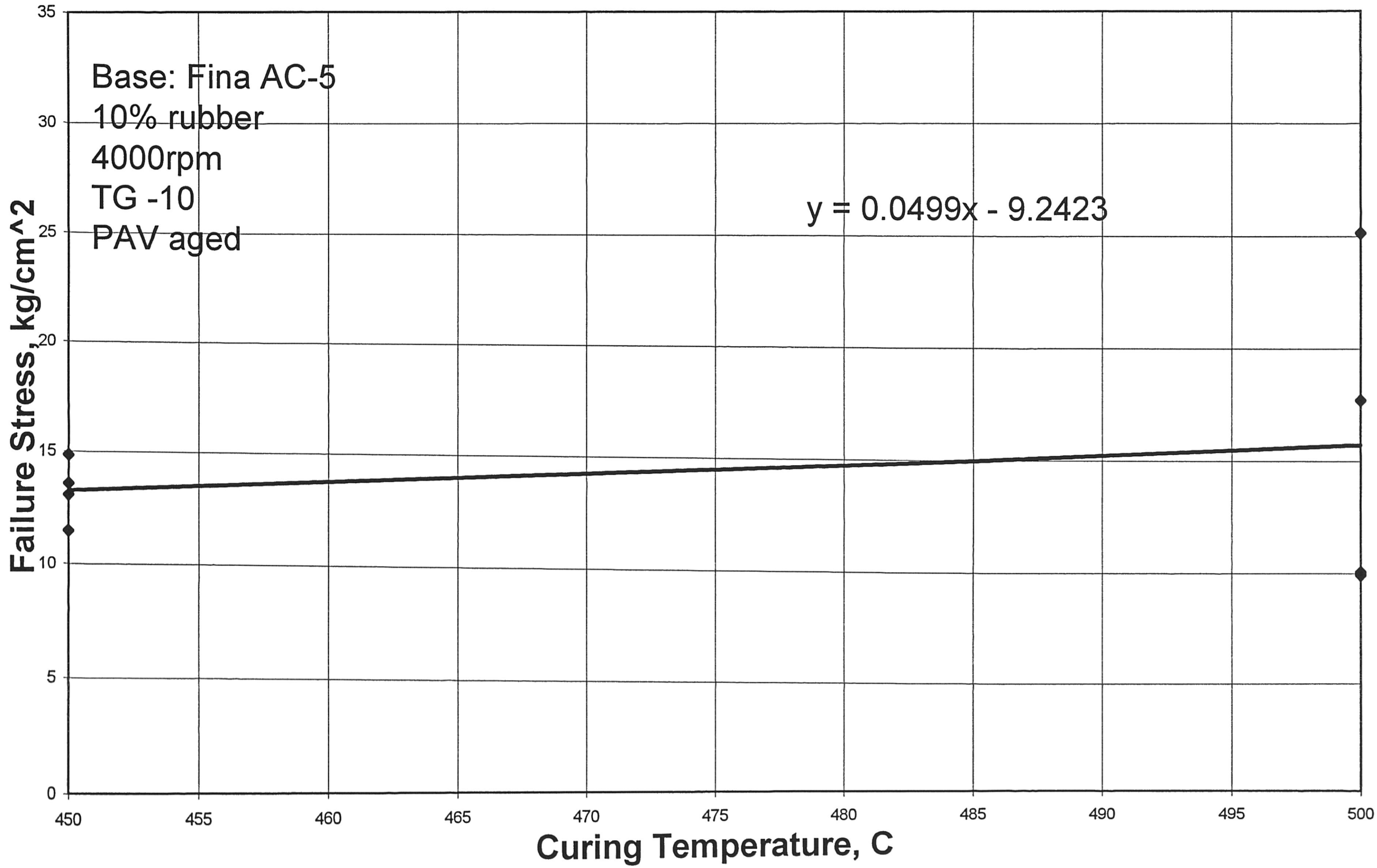

Exxon AC-10 d(f.stress)/d(curing T) -24C
Base: Exxon AC-10
10% rubber
4000rpm
TG -10
PAV aged
y = 0.1164x - 39.105
Failure Stress, kg/cm^2
35
30
25
20
15
10
5
0
450
455
460
465
470
475
480
485
490
495
500
Curing Temperature, C

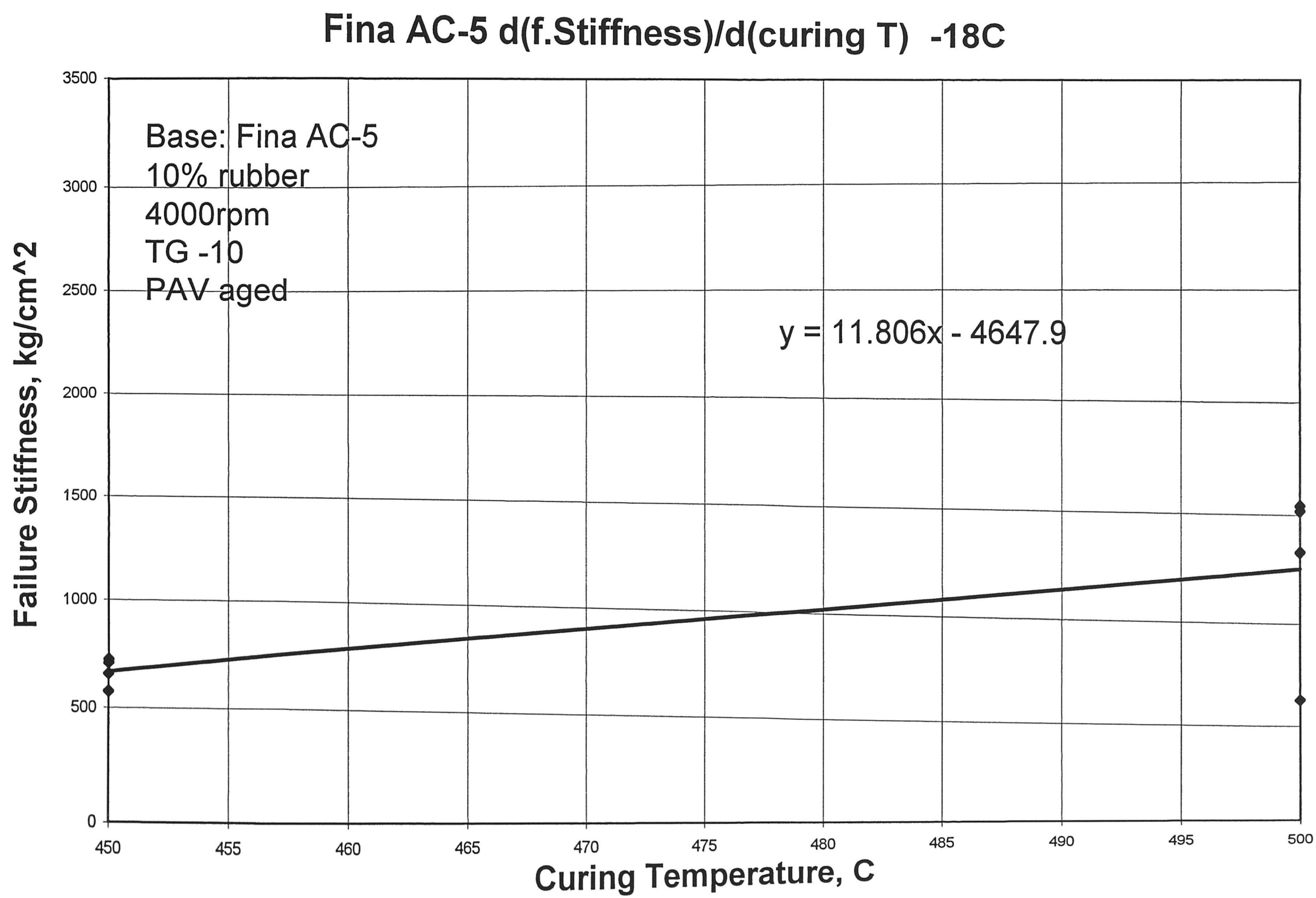

Exxon AC-10 d(f.Stiffness)/d(curing T) -24C
Base: Exxon AC-10
10% rubber
4000rpm
TG -10
PAV aged
y = 6.7026x - 1178.2
Failure Stiffness, kg/cm^2
Curing Temperature, C
3500
3000
2500
2000
1500
1000
500
0
450
455
460
465
470
475
480
485
490
495
500

Fina AC-5 d(f.strain)/d(curing T) -18C

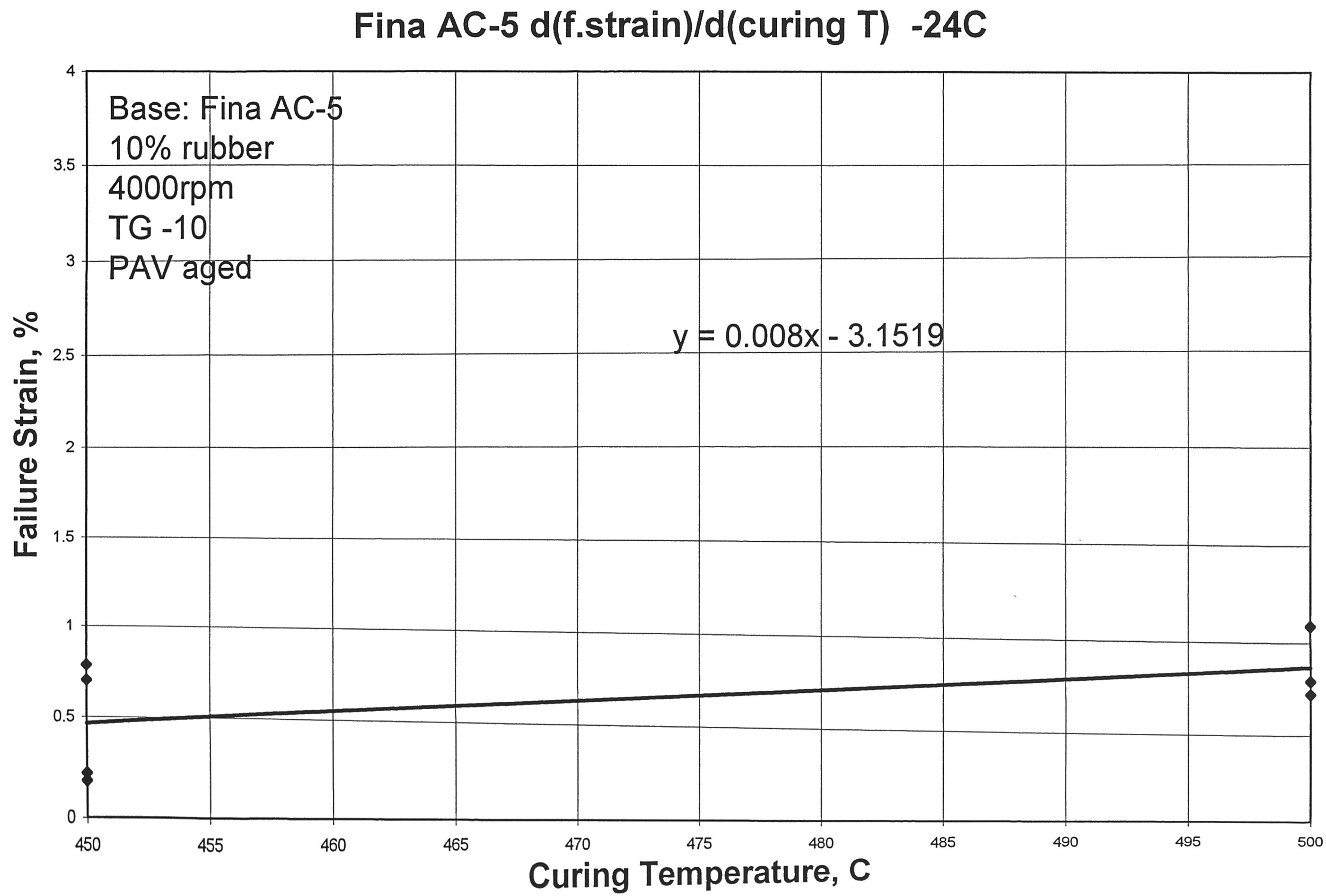


Fina AC-5 d(f.stress)/d(curing T) -18C

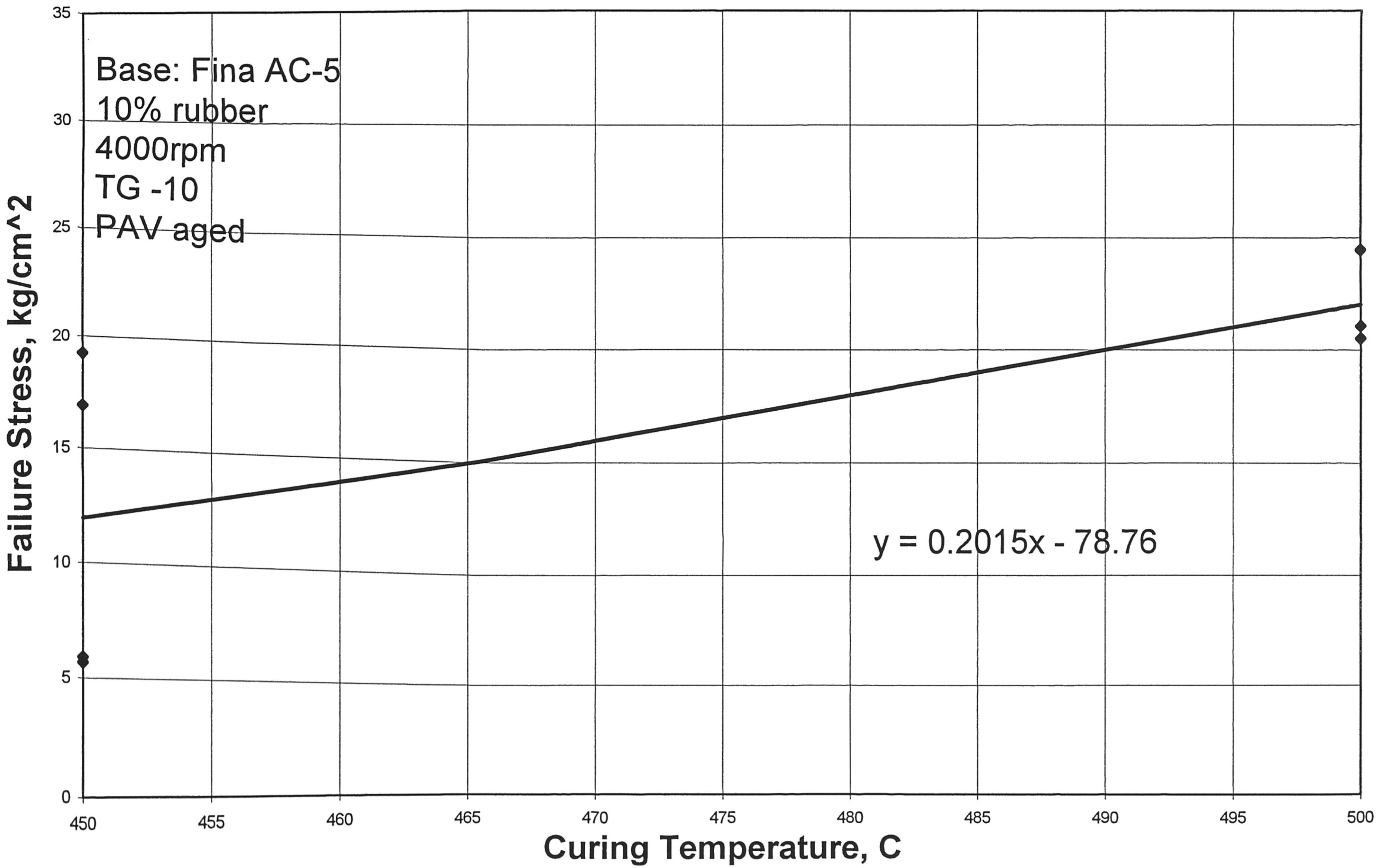


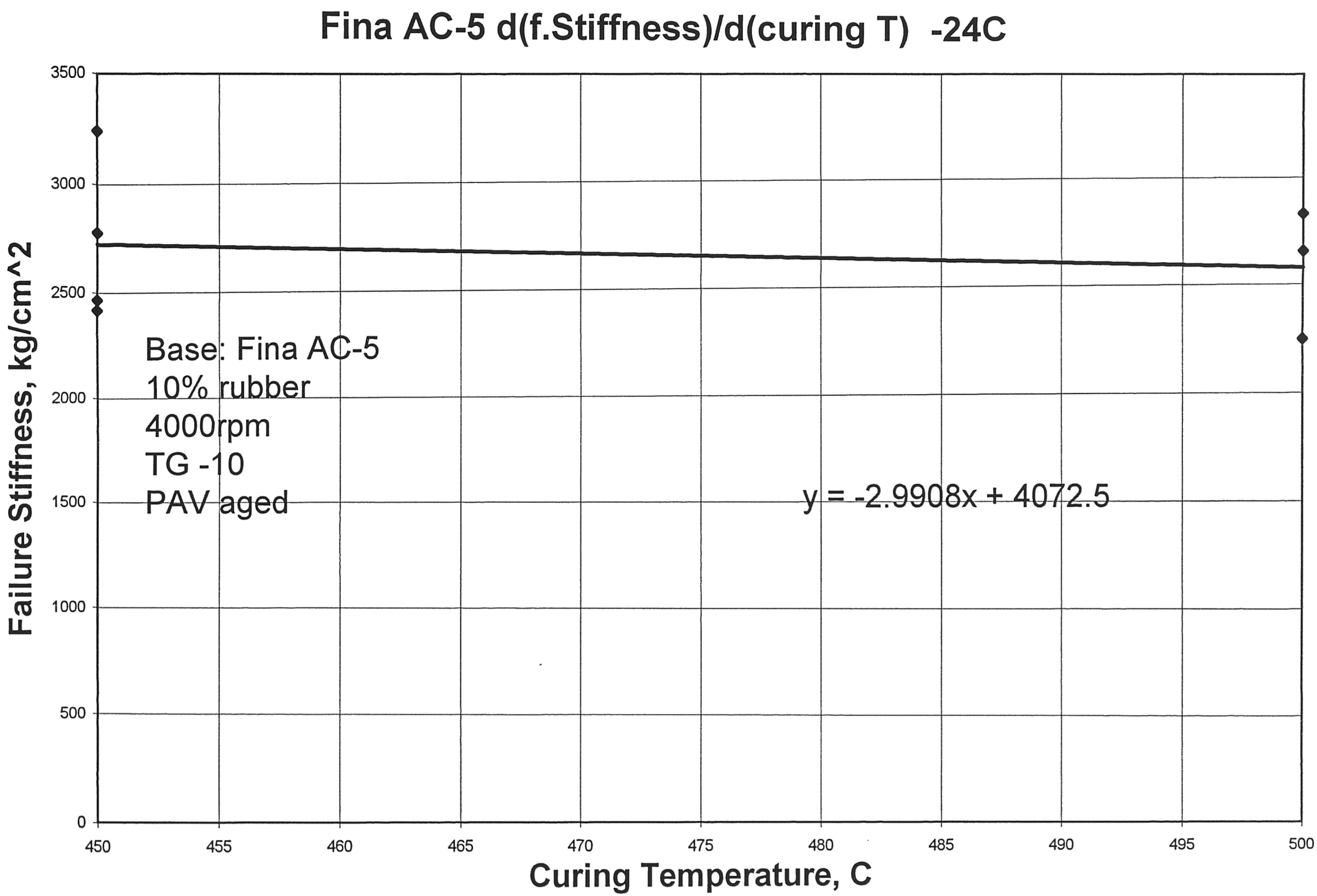


Fina AC-5 d(f.Stiffness)/d(curing T) -18C
Base: Fina AC-5
10% rubber
4000rpm
TG -10
PAV aged
y = 11.806x - 4647.9
Failure Stiffness, kg/cm^2
3500
3000
2500
2000
1500
1000
500
0
450
455
460
465
470
475
480
485
490
495
500
Curing Temperature, C

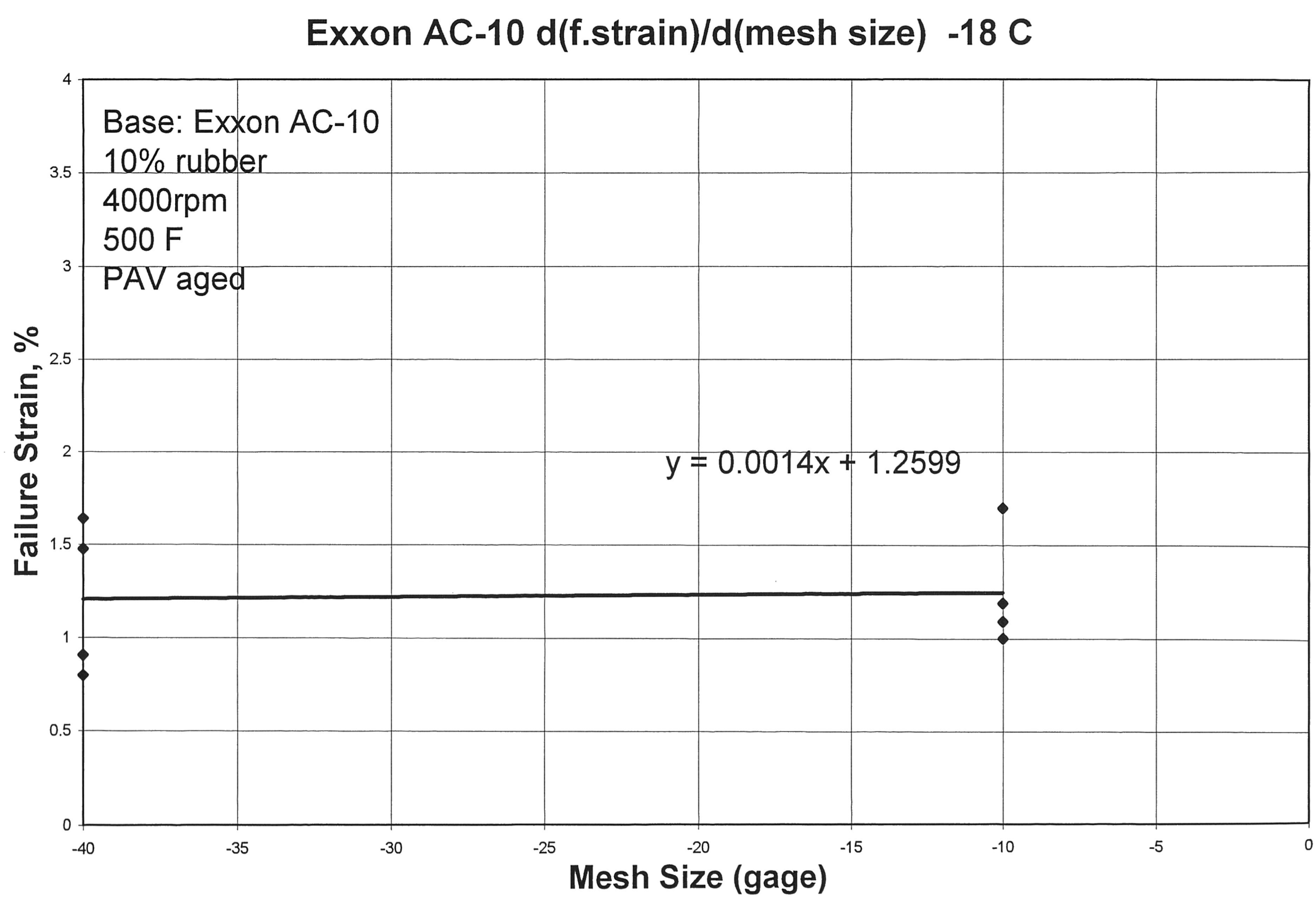

Fina AC-5 d(f.strain)/d(curing T) -24C
Base: Fina AC-5
10% rubber
4000rpm
TG -10
PAV aged
y = 0.008x - 3.1519
Failure Strain, %
Curing Temperature, C
0
0.5
1
1.5
2
2.5
3
3.5
4
450
455
460
465
470
475
480
485
490
495
500

Fina AC-5 d(f.stress)/d(curing T) -24C

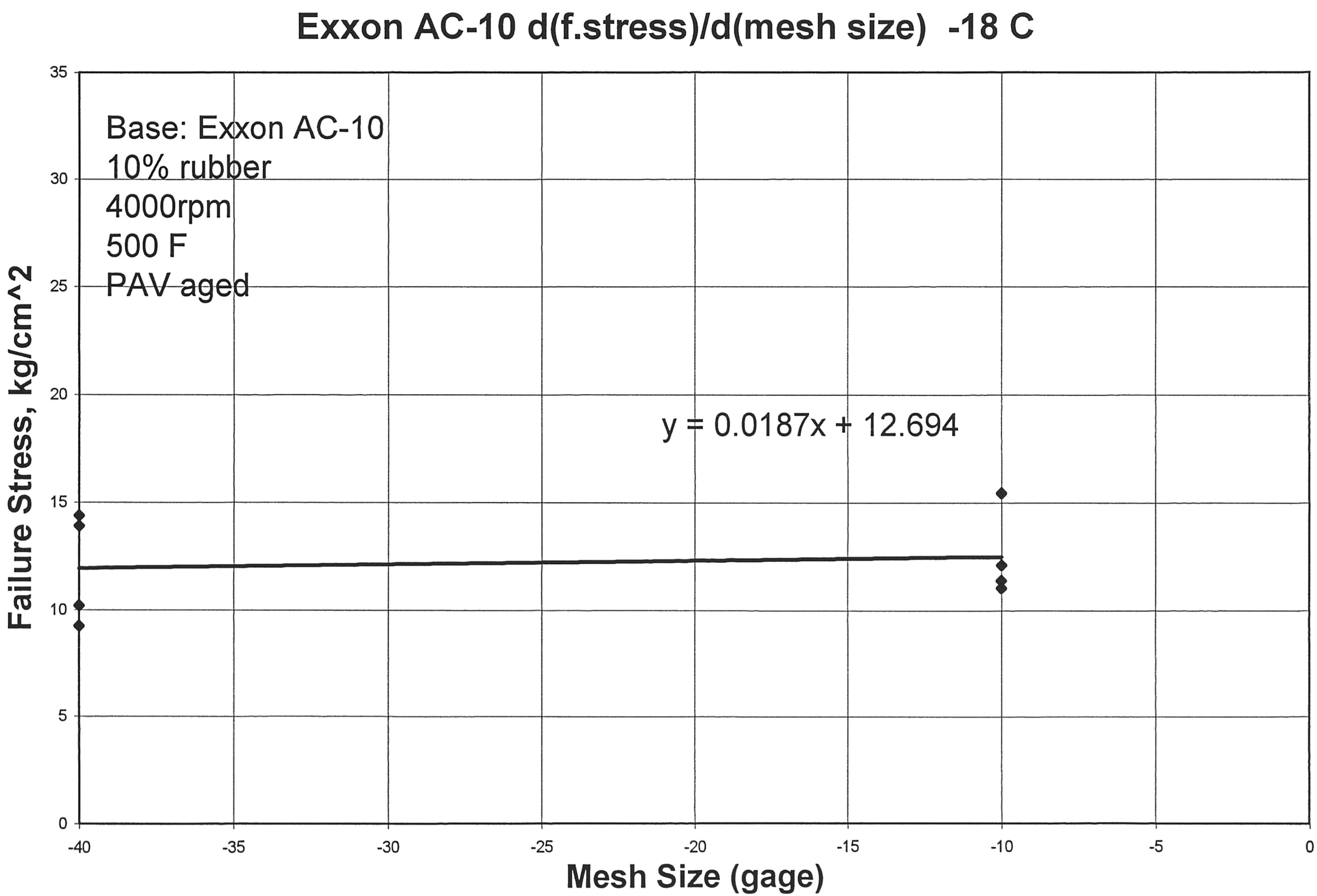


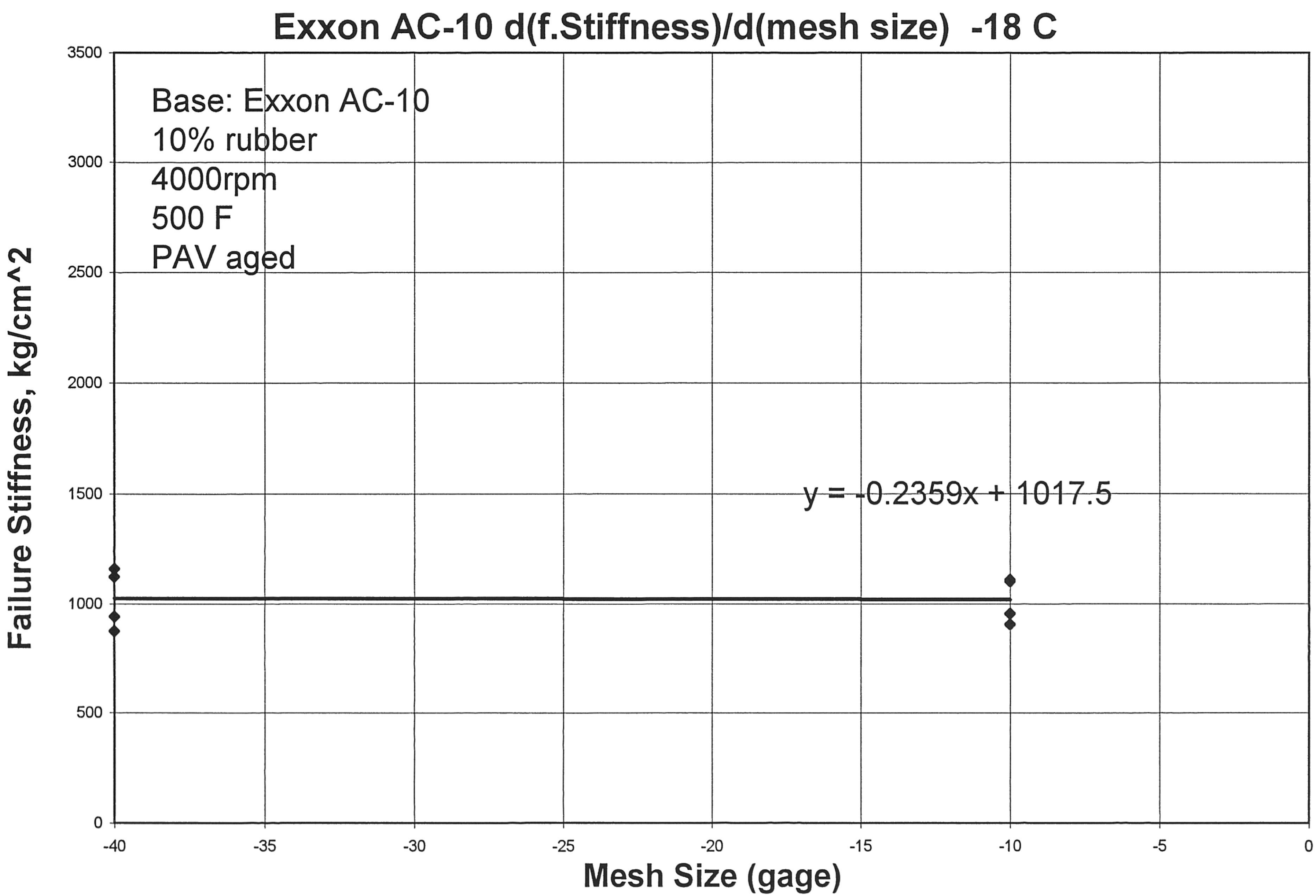


Fina AC-5 d(f.Stiffness)/d(curing T) -24C
Failure Stiffness, kg/cm^2
3500
3000
2500
2000
1500
1000
500
0
450
455
460
465
470
475
480
485
490
495
500
Curing Temperature, C
Base: Fina AC-5
10% rubber
4000rpm
TG -10
PAV aged
y = -2.9908x + 4072.5



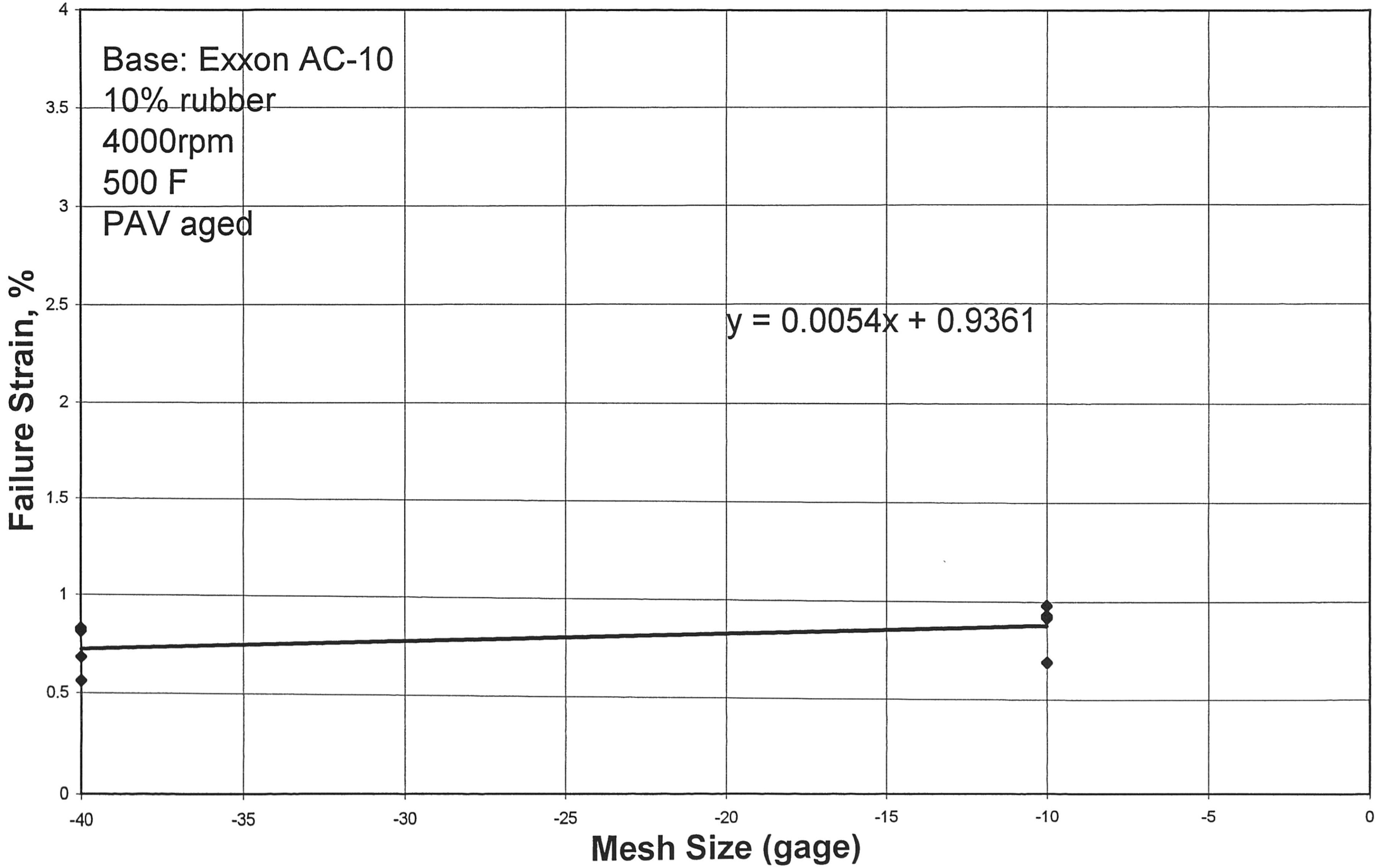
Exxon AC-10 d(f.strain)/d(mesh size) -18 C
Base: Exxon AC-10
10% rubber
4000rpm
500 F
PAV aged
y = 0.0014x + 1.2599
Failure Strain, %
Mesh Size (gage)
4
3.5
3
2.5
2
1.5
1
0.5
0
-40
-35
-30
-25
-20
-15
-10
-5
0

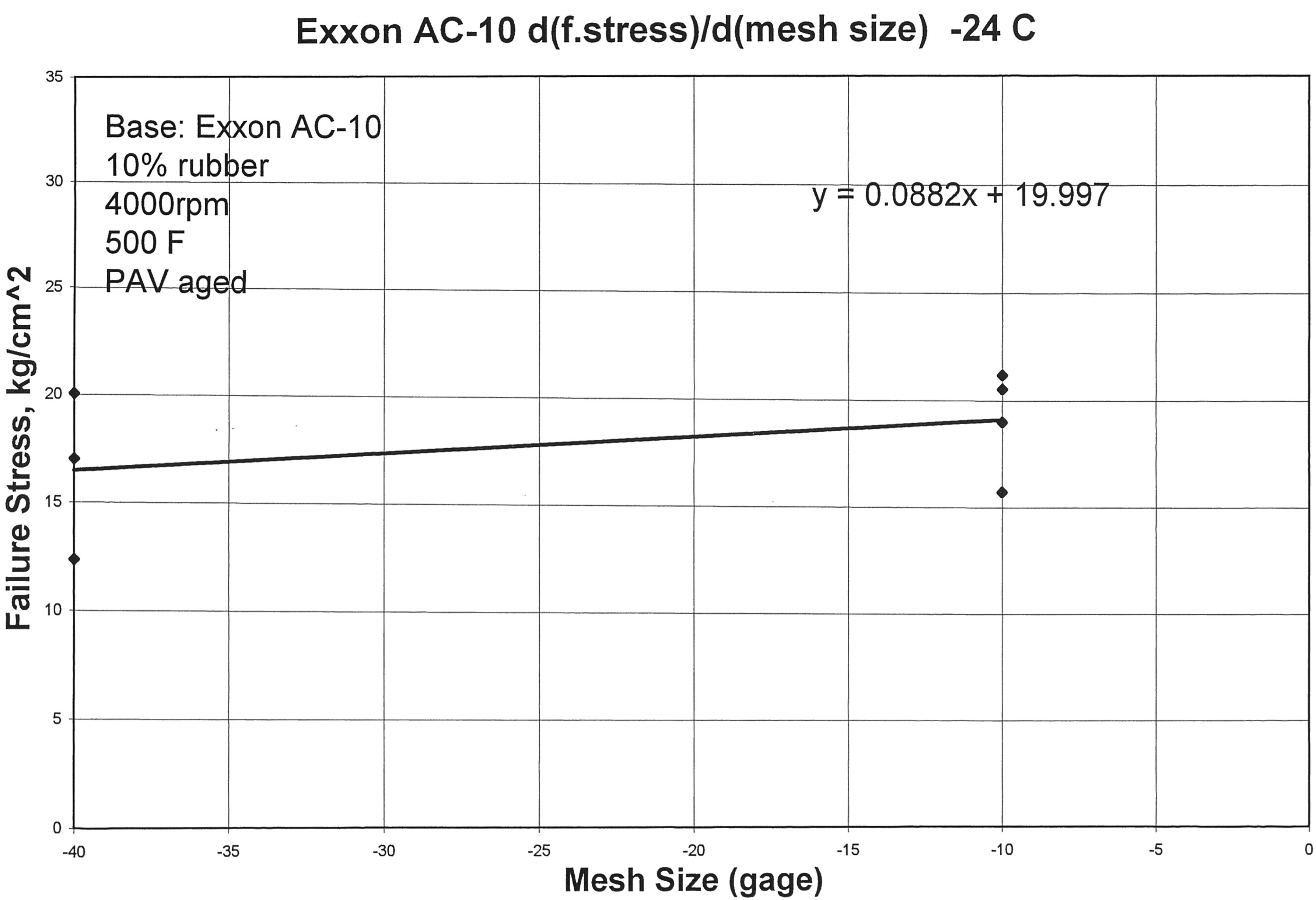

Exxon AC-10 d(f.stress)/d(mesh size) -18 C
Base: Exxon AC-10
10% rubber
4000rpm
500 F
PAV aged
y = 0.0187x + 12.694
Failure Stress, kg/cm^2
Mesh Size (gage)
35
30
25
20
15
10
5
0
-40
-35
-30
-25
-20
-15
-10
-5
0

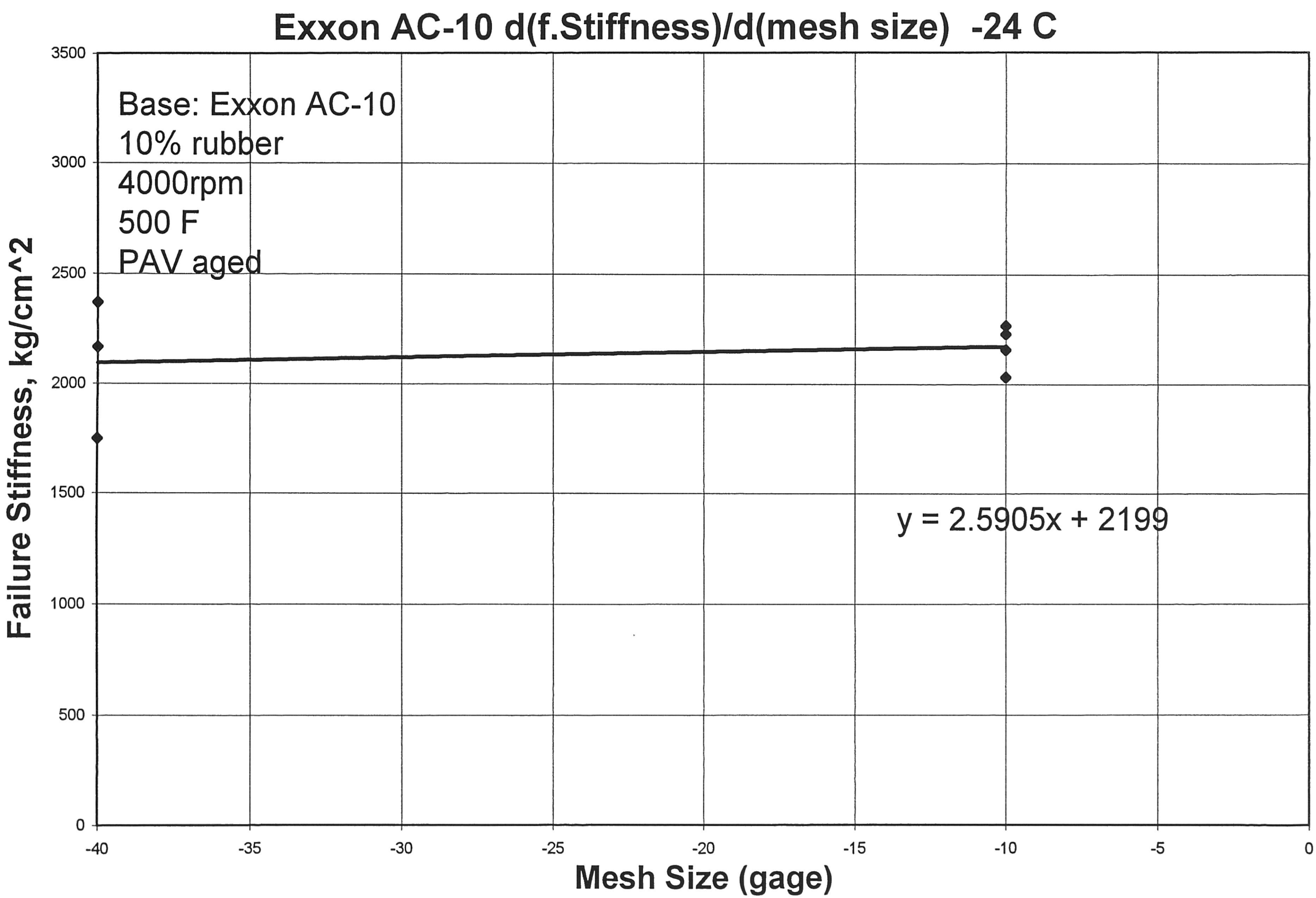


Exxon AC-10 d(f.Stiffness)/d(mesh size) -18 C
Base: Exxon AC-10
10% rubber
4000rpm
500 F
PAV aged
y = -0.2359x + 1017.5
Failure Stiffness, kg/cm^2
3500
3000
2500
2000
1500
1000
500
0
-40
-35
-30
-25
-20
-15
-10
-5
0
Mesh Size (gage)

Exxon AC-10 d(f.strain)/d(mesh size) -24 C

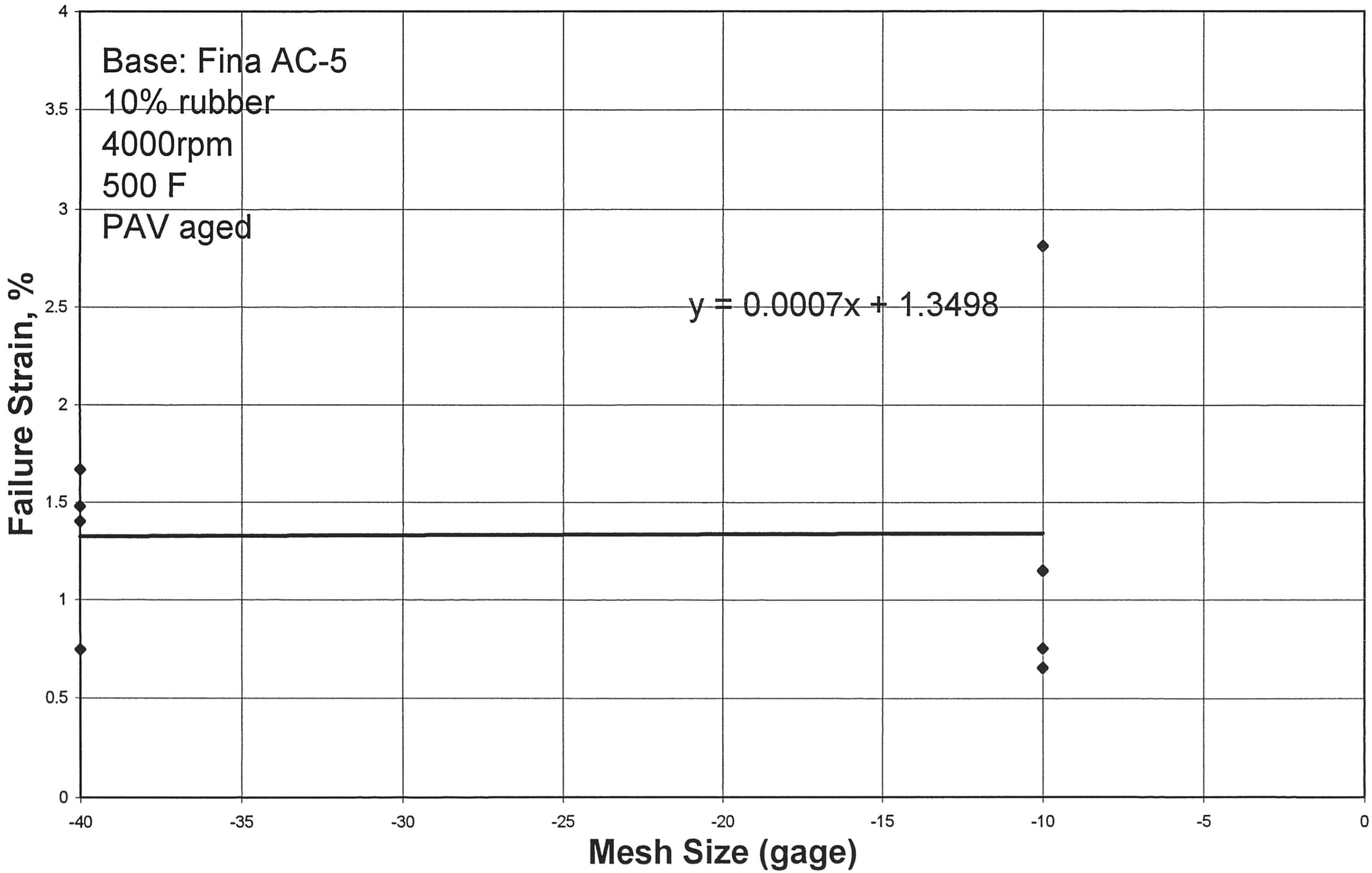


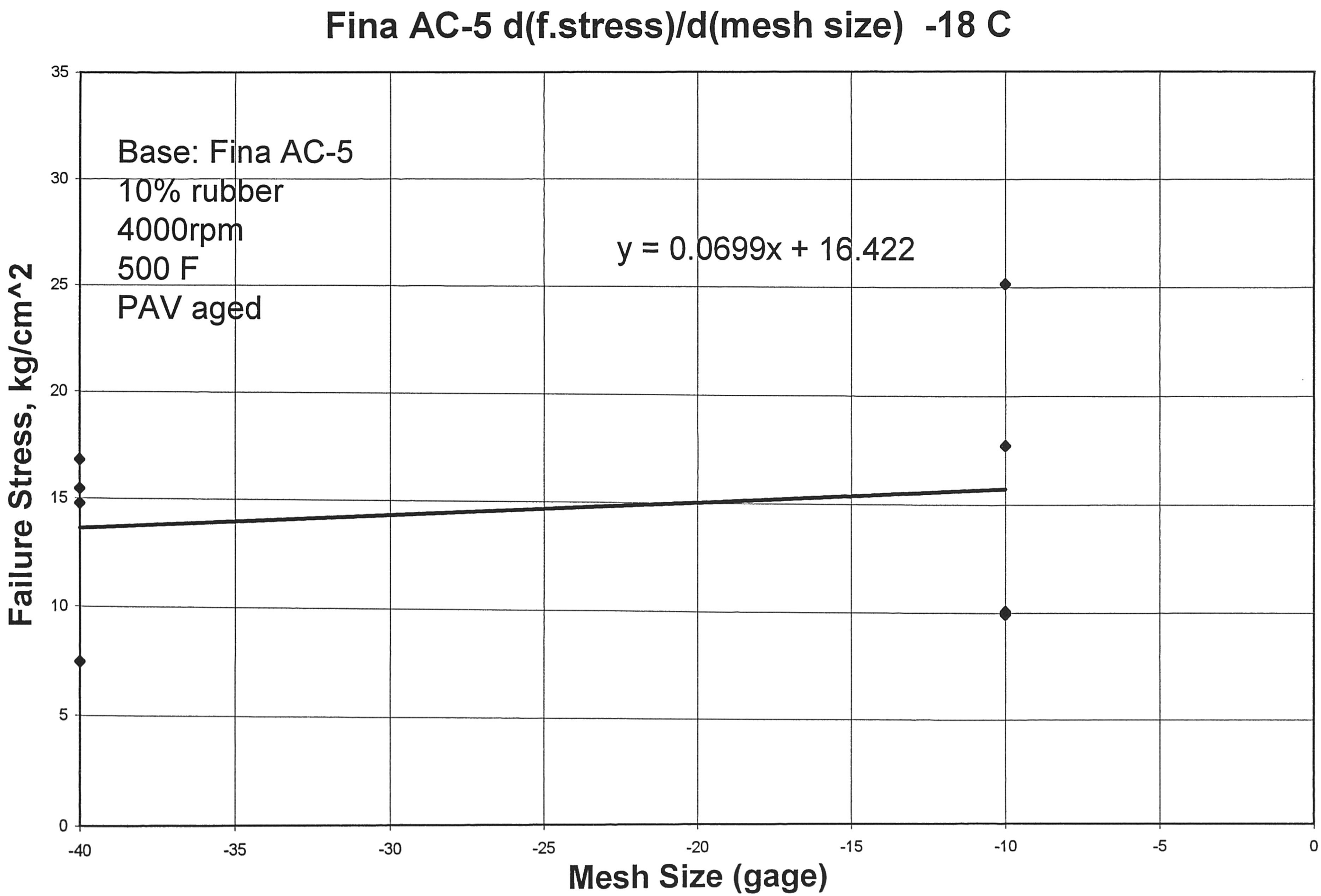

Exxon AC-10 d(f.stress)/d(mesh size) -24 C
Base: Exxon AC-10
10% rubber
4000rpm
500 F
PAV aged
y = 0.0882x + 19.997
Failure Stress, kg/cm^2
Mesh Size (gage)
35
30
25
20
15
10
5
0
-40
-35
-30
-25
-20
-15
-10
-5
0



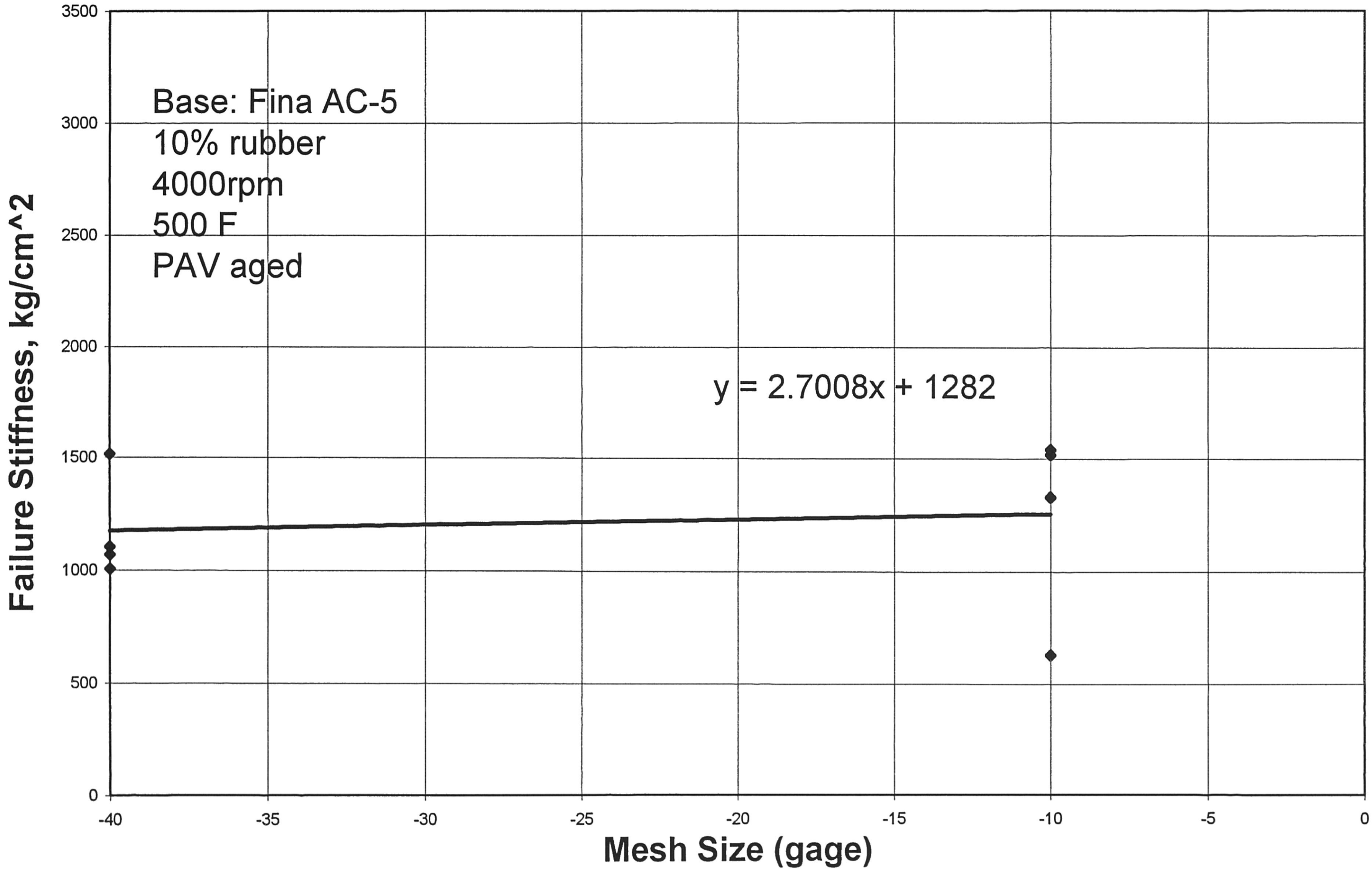
Exxon AC-10 d(f.Stiffness)/d(mesh size) -24 C
Base: Exxon AC-10
10% rubber
4000rpm
500 F
PAV aged
y = 2.5905x + 2199
Failure Stiffness, kg/cm^2
Mesh Size (gage)
3500
3000
2500
2000
1500
1000
500
0
-40
-35
-30
-25
-20
-15
-10
-5
0

Fina AC-5 d(f.strain)/d(mesh size) -18 C

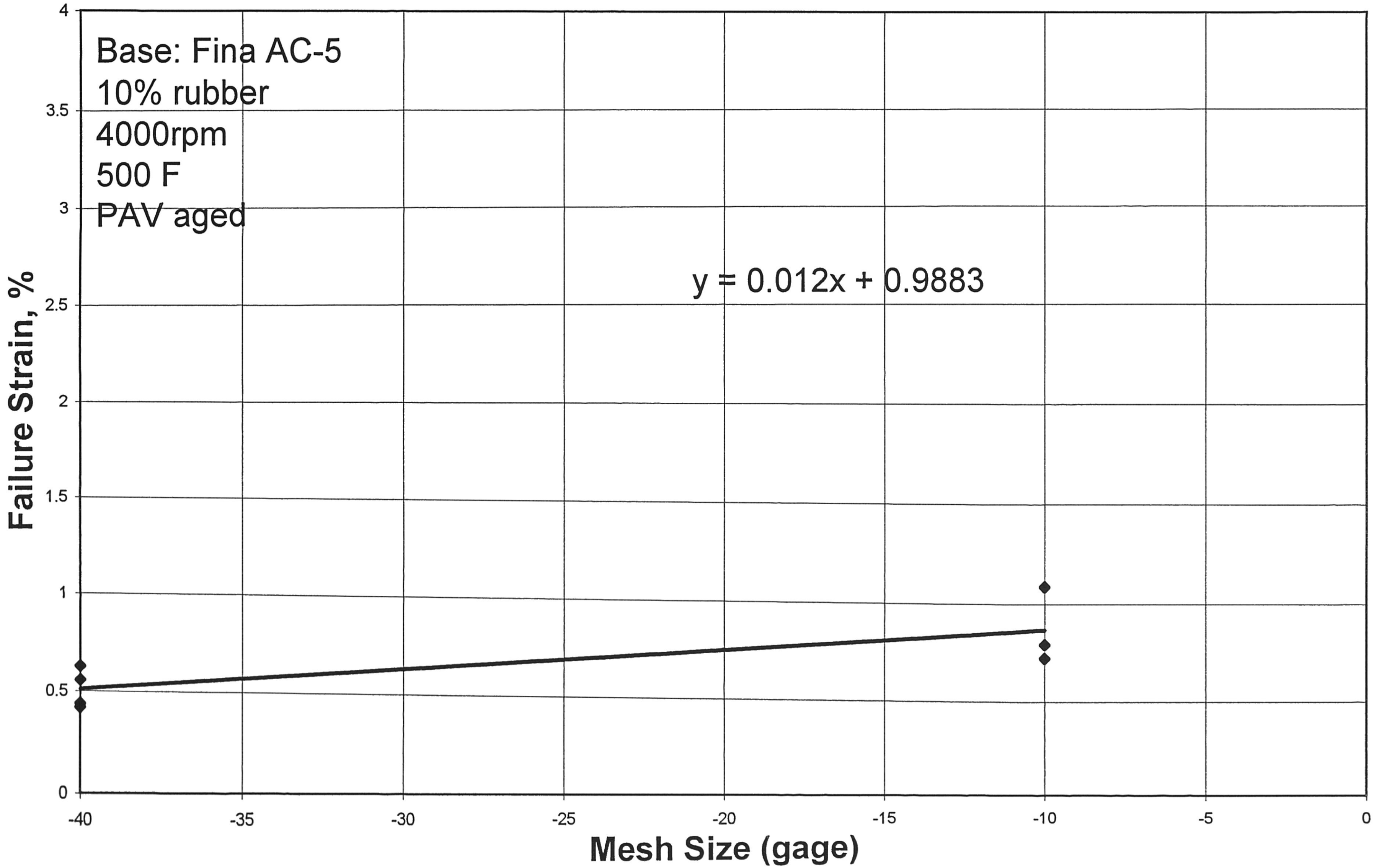


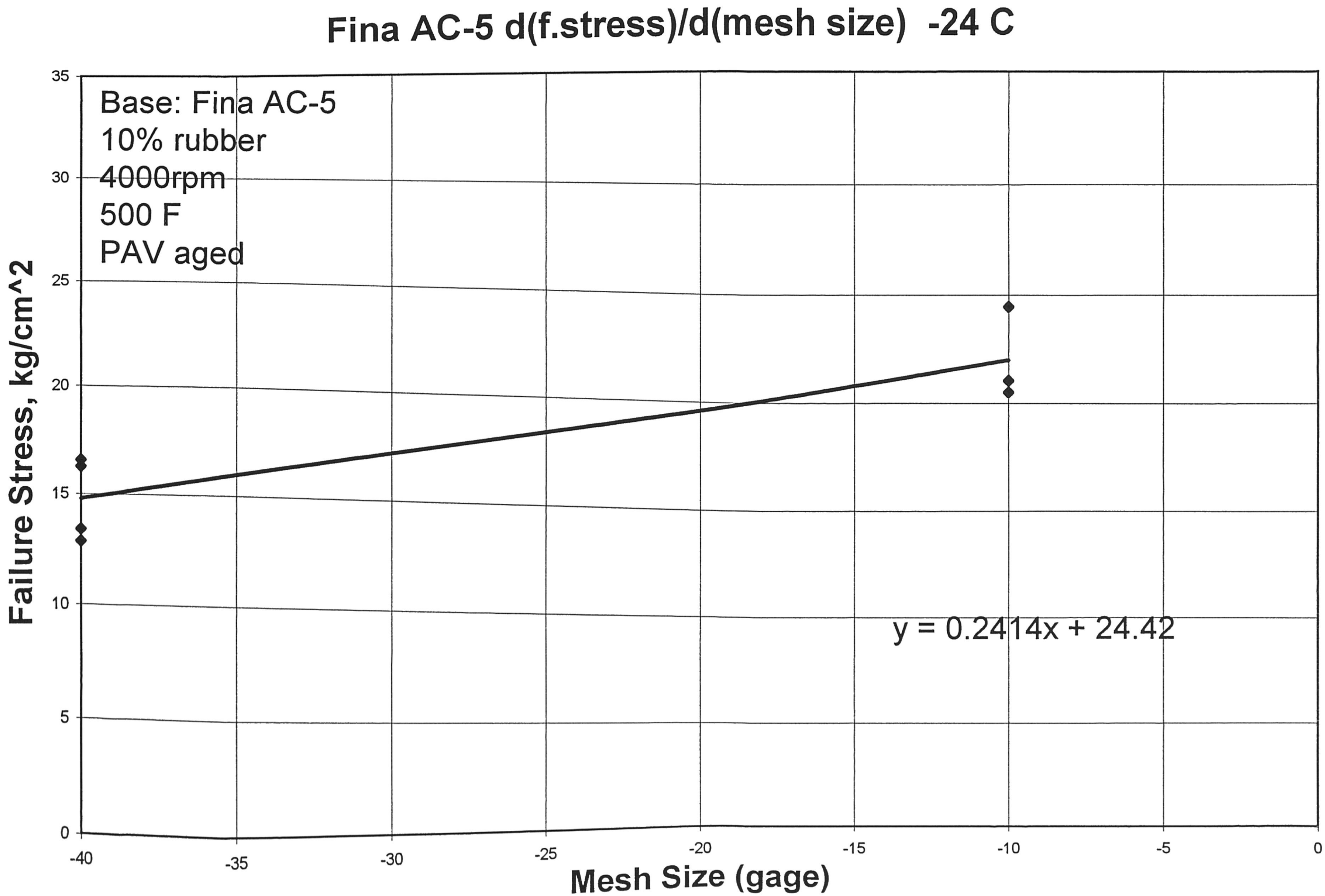

Fina AC-5 d(f.stress)/d(mesh size) -18 C
Base: Fina AC-5
10% rubber
4000rpm
500 F
PAV aged
y = 0.0699x + 16.422
Failure Stress, kg/cm^2
Mesh Size (gage)
35
30
25
20
15
10
5
0
-40
-35
-30
-25
-20
-15
-10
-5
0

Fina AC-5 d(f.Stiffness)/d(mesh size) -18 C



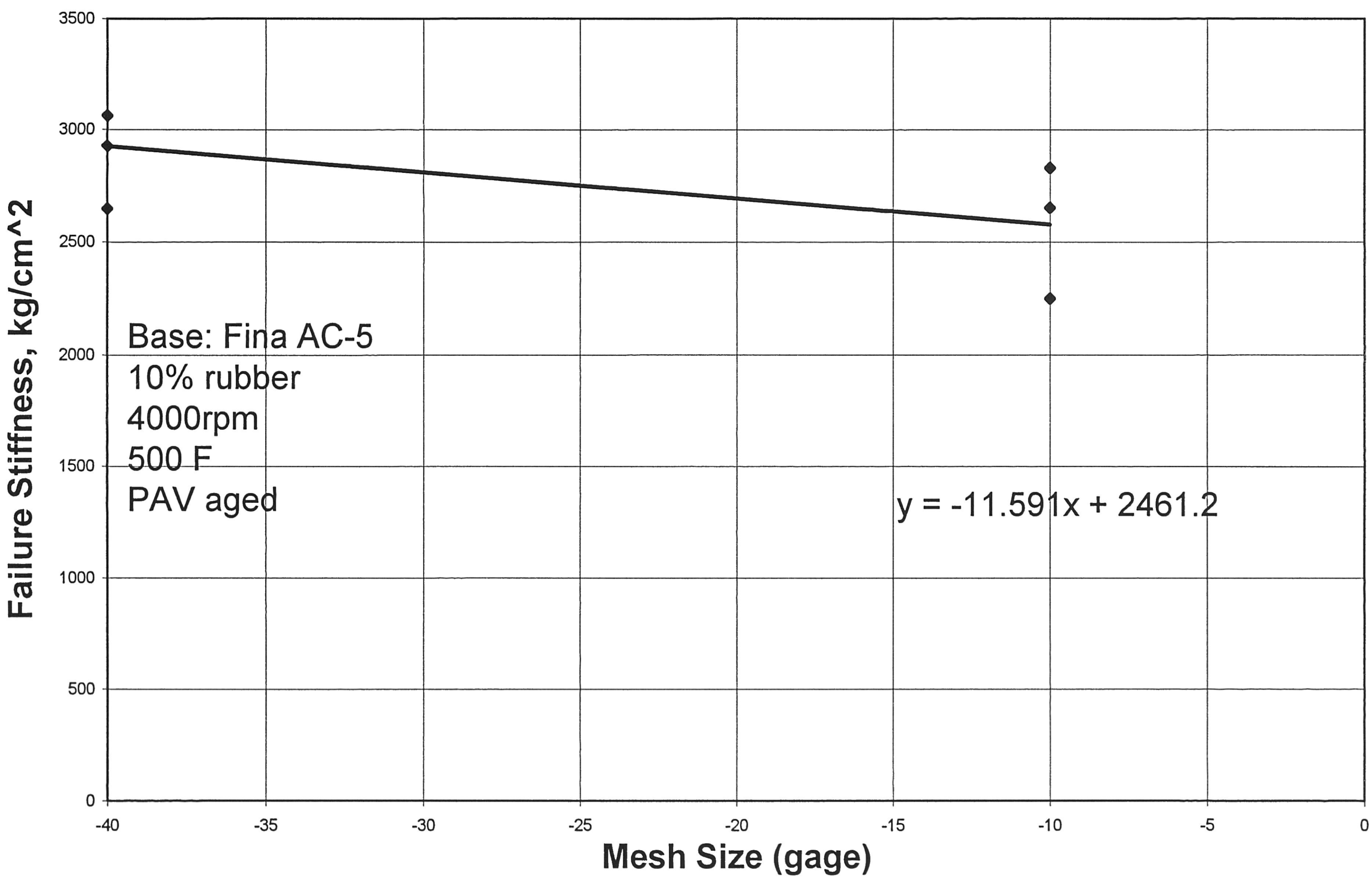
Fina AC-5 d(f.strain)/d(mesh size) -24 C



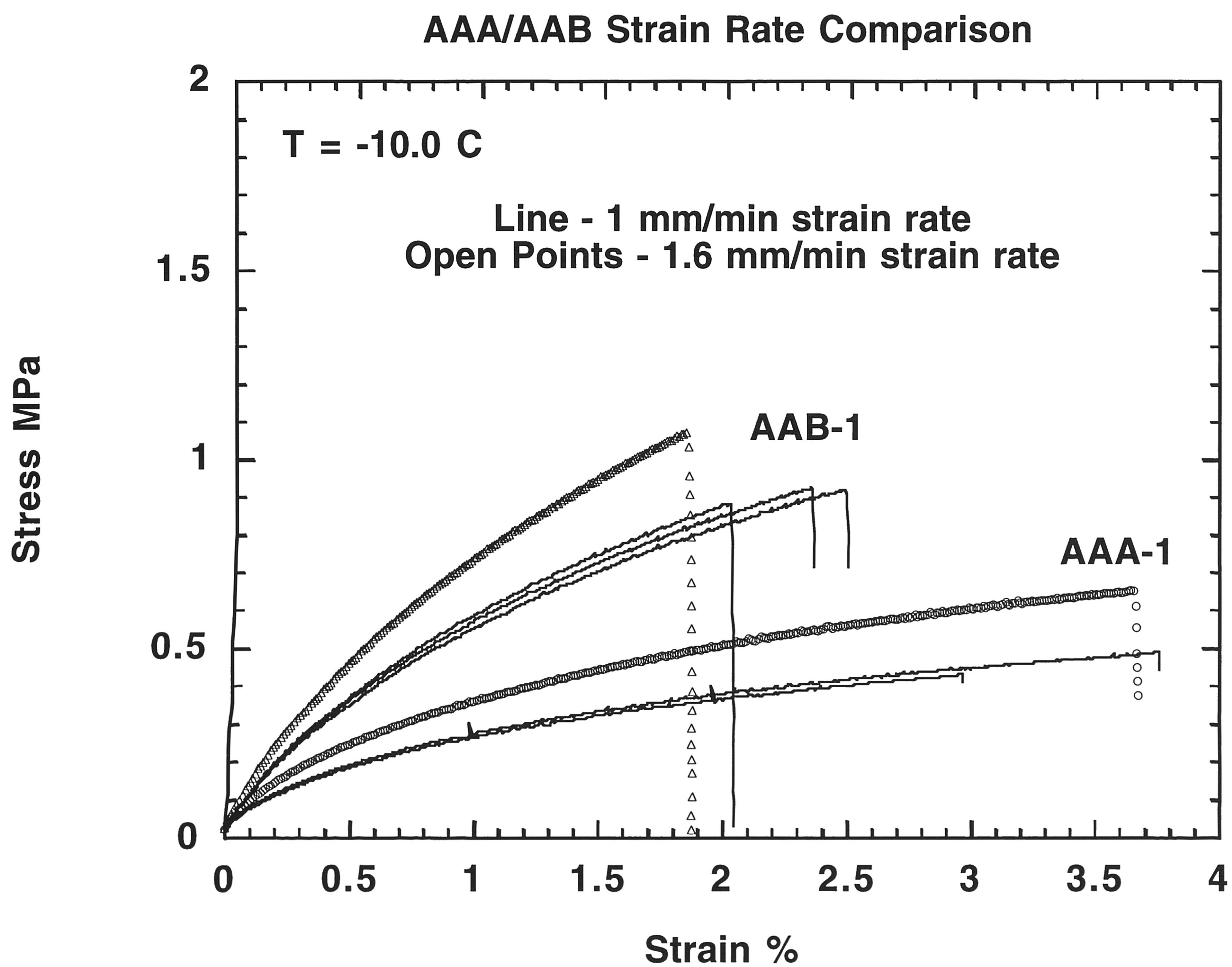


Fina AC-5 d(f.stress)/d(mesh size) -24 C
Base: Fina AC-5
10% rubber
4000rpm
500 F
PAV aged
y = 0.2414x + 24.42
Failure Stress, kg/cm^2
Mesh Size (gage)
35
30
25
20
15
10
5
0
-40
-35
-30
-25
-20
-15
-10
-5
0

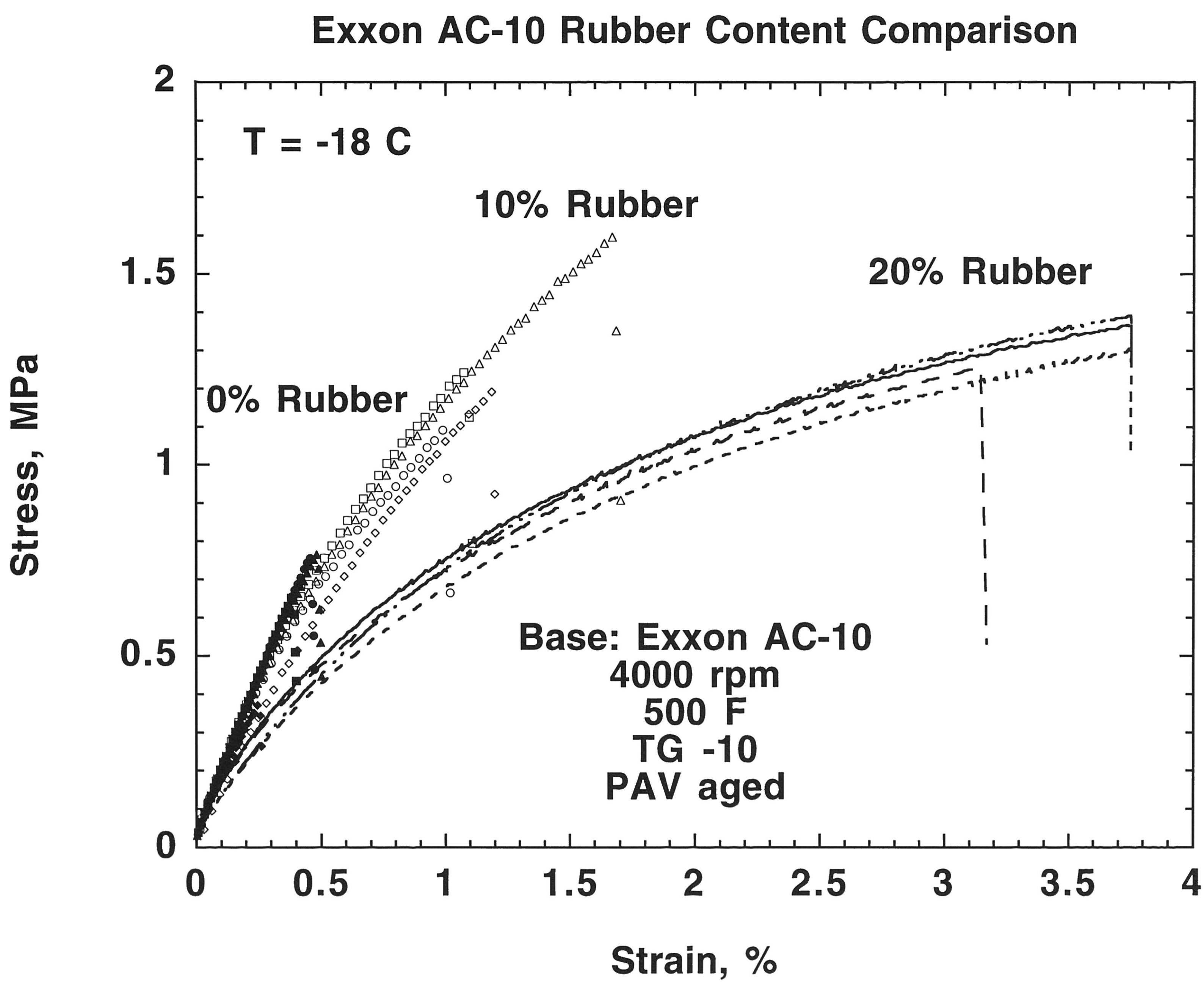
Fina AC-5 d(f.Stiffness)/d(mesh size) -24 C

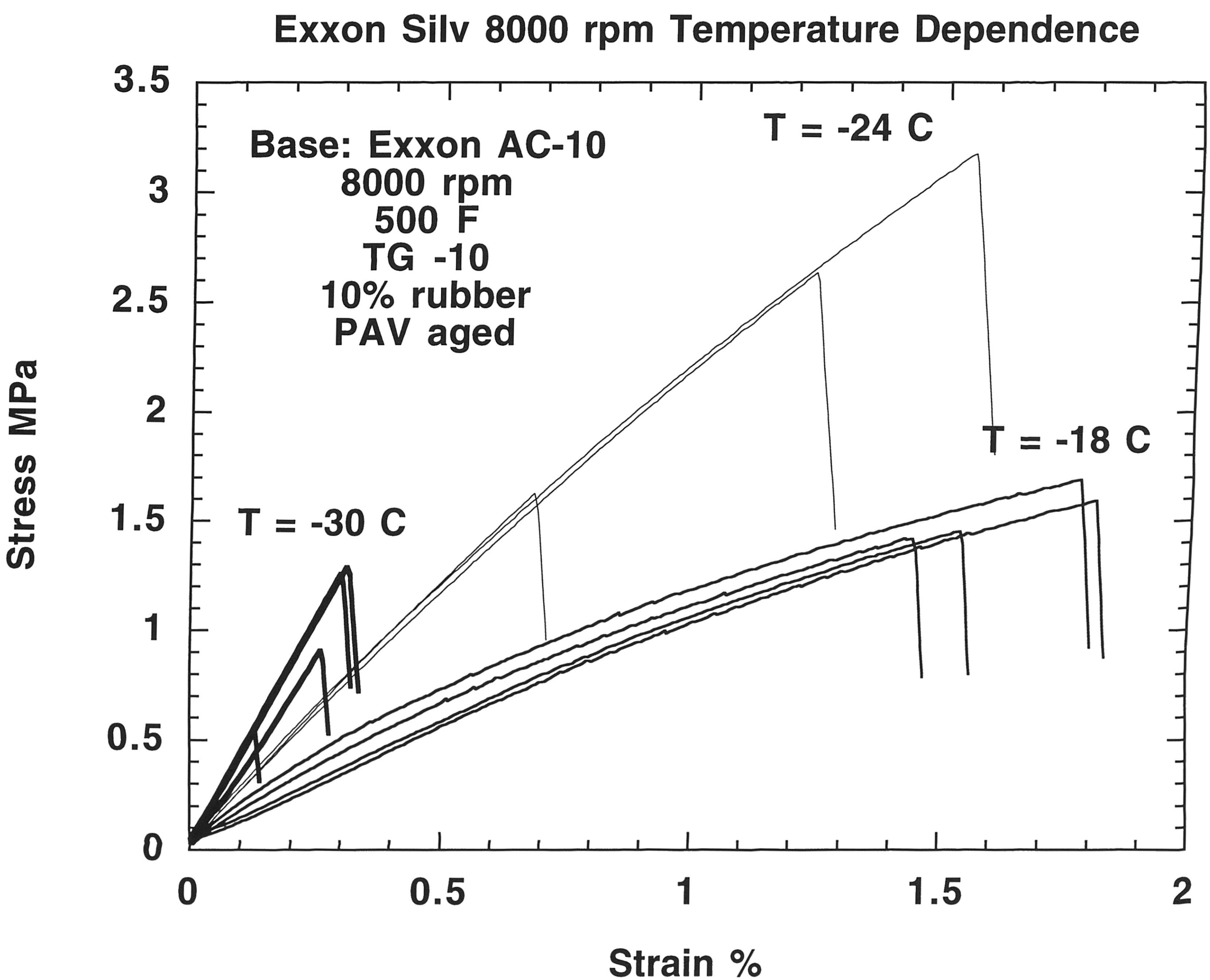


Appendix J: Additional Stress-Strain Curves



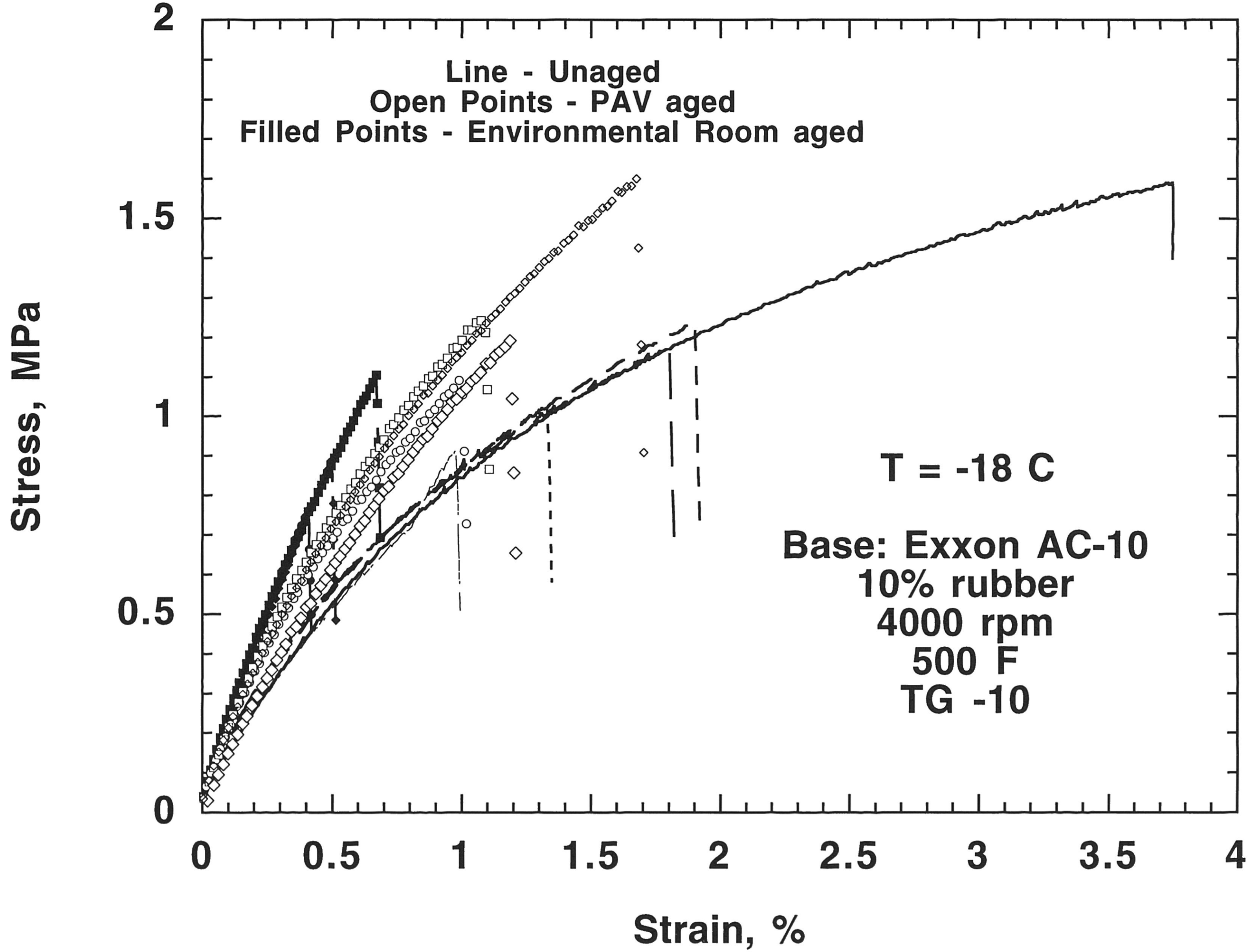
AAA/AAB Strain Rate Comparison
T = -10.0 C
Line - 1 mm/min strain rate
Open Points - 1.6 mm/min strain rate
AAB-1
AAA-1
Stress MPa
Strain %
2
1.5
1
0.5
0
0.5
1
1.5
2
2.5
3
3.5
4

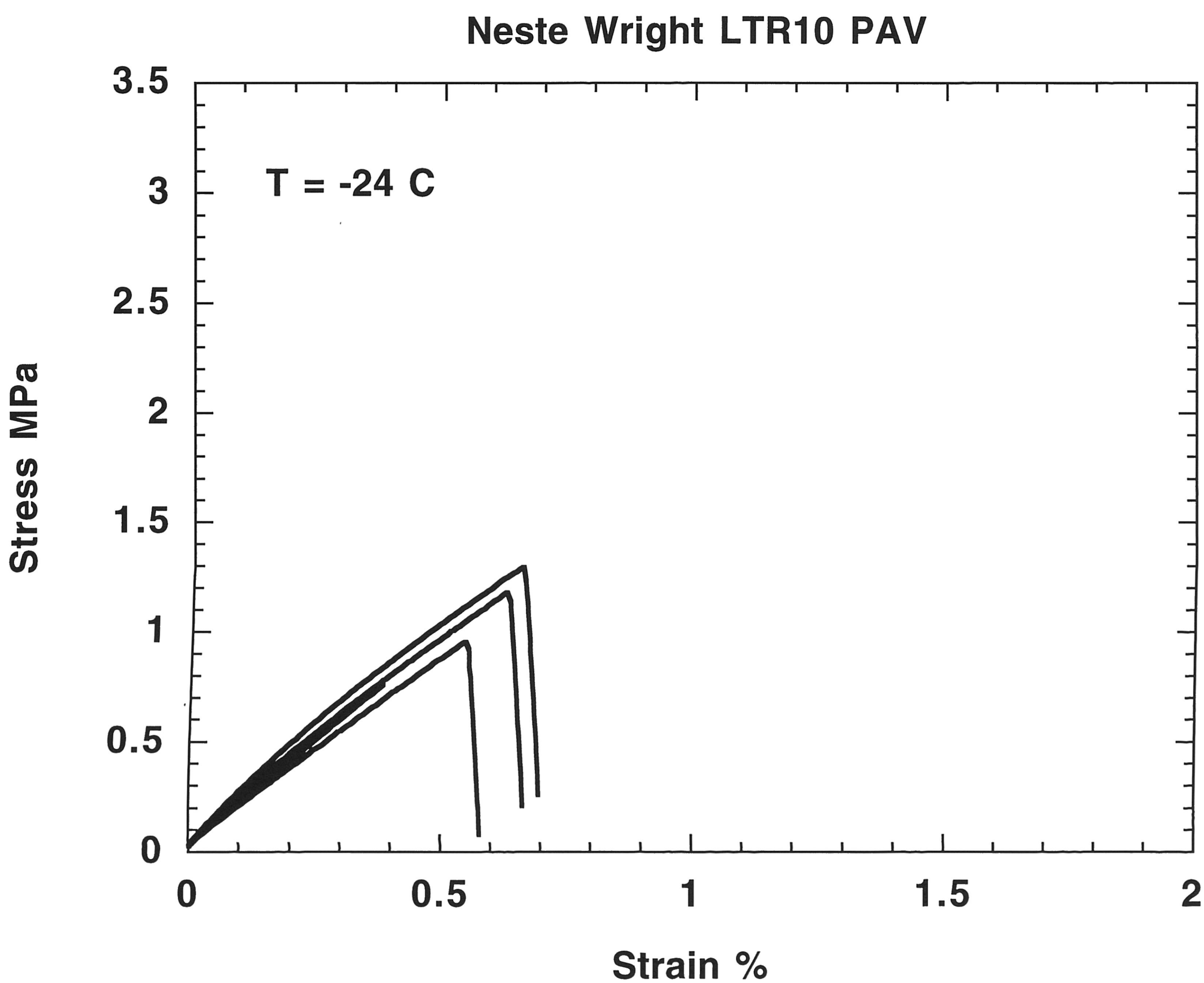

Exxon AC-10 Rubber Content Comparison
T = -18 C
10% Rubber
20% Rubber
0% Rubber
Base: Exxon AC-10
4000 rpm
500 F
TG -10
PAV aged
Stress, MPa
Strain, %
0
0.5
1
1.5
2
2.5
3
3.5
4



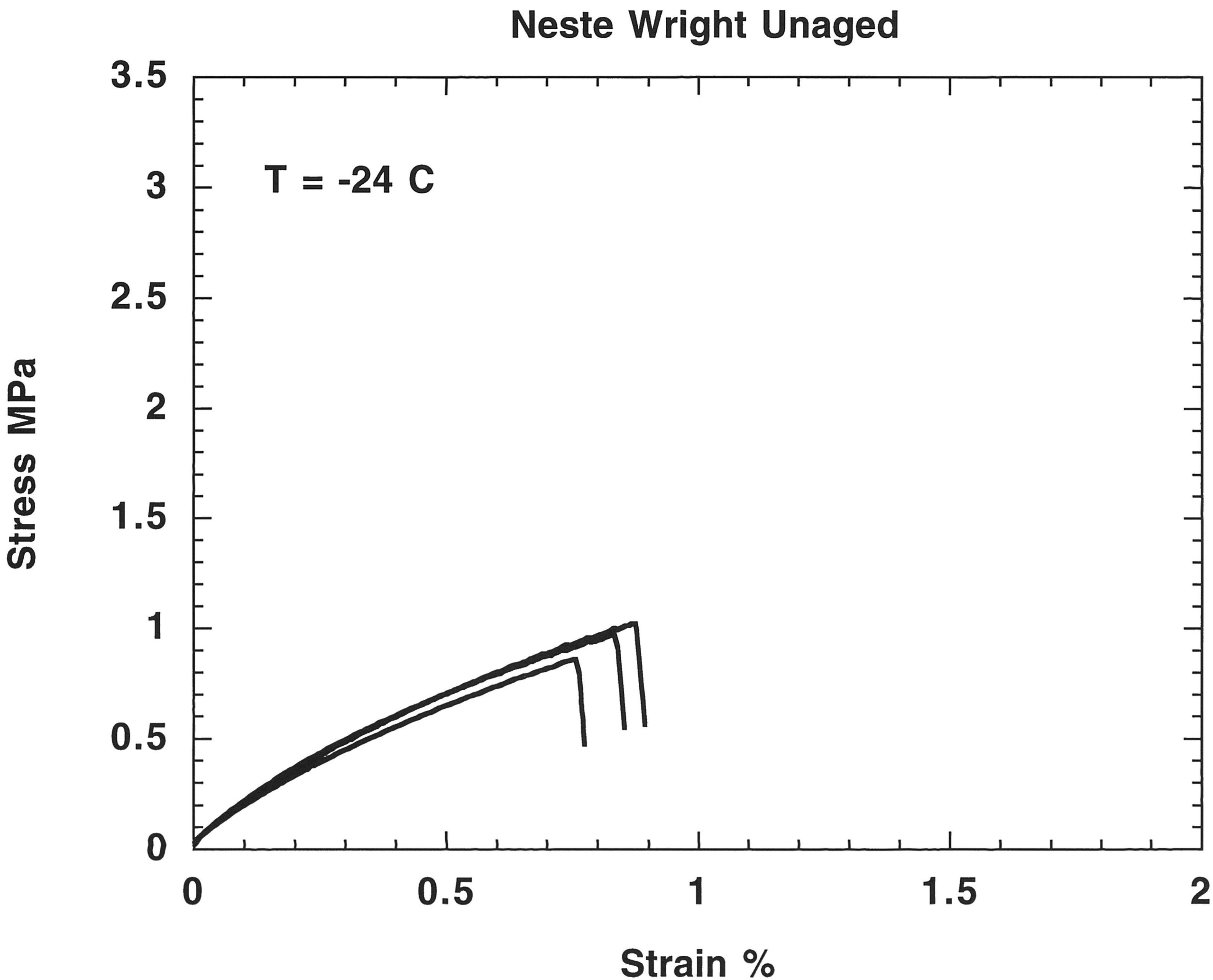
Exxon Silv 8000 rpm Temperature Dependence
Base: Exxon AC-10
8000 rpm
500 F
TG -10
10% rubber
PAV aged
T = -24 C
T = -18 C
T = -30 C
Stress MPa
Strain %
3.5
3
2.5
2
1.5
1
0.5
0
0
0.5
1
1.5
2

Exxon AC-10 Aging Comparison

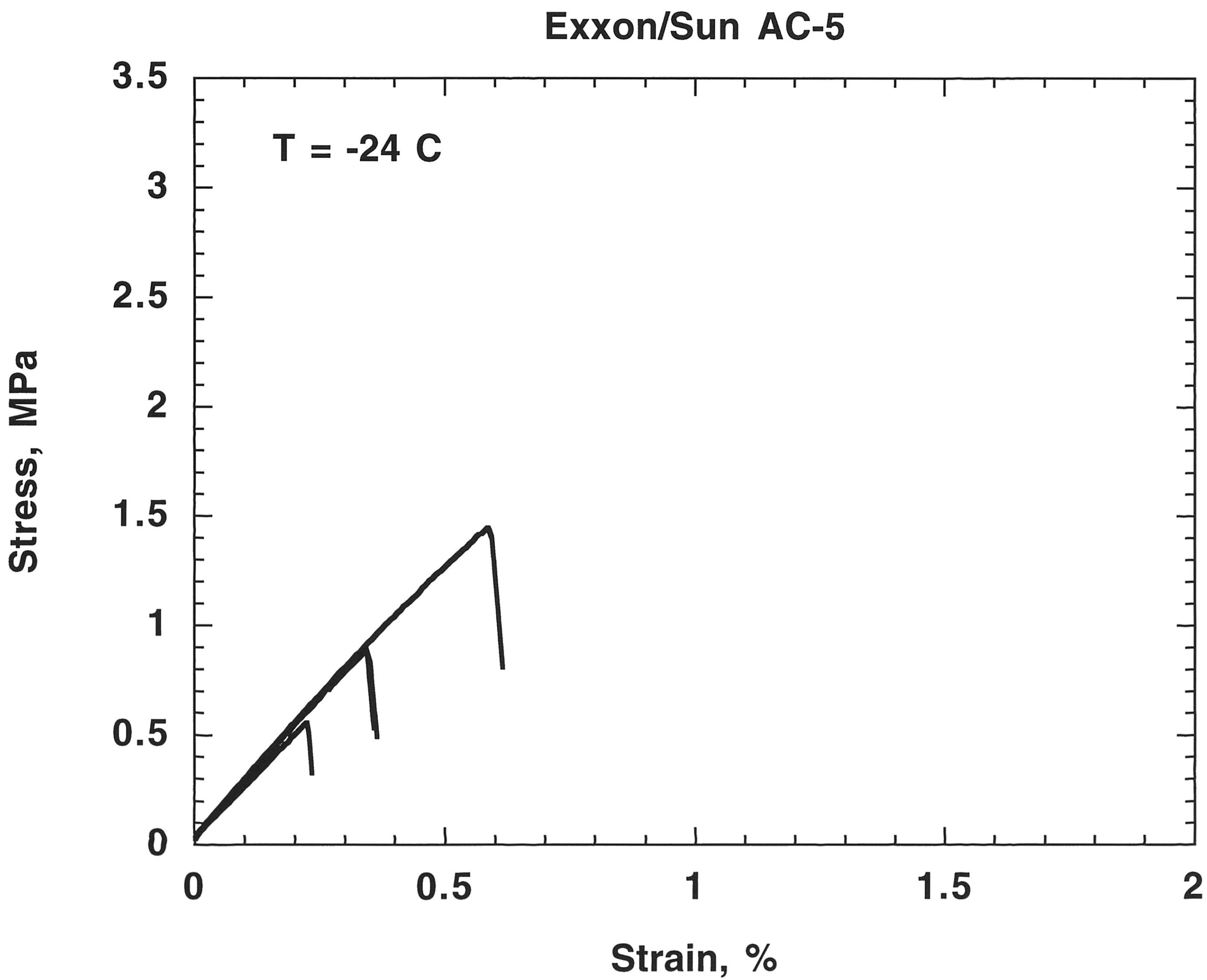




Neste Wright LTR10 PAV
T = -24 C
Stress MPa
Strain %
0
0.5
1
1.5
2
2.5
3
3.5



Neste Wright Unaged
T = -24 C
Stress MPa
Strain %
3.5
3
2.5
2
1.5
1
0.5
0
0.5
1
1.5
2



Exxon/Sun AC-5
T = -24 C
3.5
3
2.5
2
1.5
1
0.5
0
Stress, MPa
0
0.5
1
1.5
2
Strain, %